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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Learning from Experience. Volume 2. Lessons from the U.S. Navy's Ohio, Seawolf, and Virginia Submarine Programs**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **RAND Corporation,National Defense Research Institute,1776 Main Street, P.O. Box 2138,Santa Monica,CA,90407-2138**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**155**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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LEARNING FROM EXPERIENCE

VOLUME II

Lessons from the U.S. Navy's *Ohio*, *Seawolf*, and *Virginia* Submarine Programs

Prepared for the United States Navy

Approved for public release; distribution unlimited

RAND NATIONAL DEFENSE RESEARCH INSTITUTE

The research described in this report was prepared for the United States Navy. The research was conducted within the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community under Contract W74V8H-06-C-0002.

Library of Congress Control Number: 2011939404

ISBN: 978-0-8330-5896-6

Published 2011 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
4570 Fifth Avenue, Suite 600, Pittsburgh, PA 15213-2665
RAND URL: http://www.rand.org
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Preface

The successful conduct of large, complex design and construction programs requires personnel with unique skills and capabilities supplemented with practical experience in their areas of expertise. This is especially true for the design and construction of new nuclear powered submarines. Unique design and engineering skills must be nurtured and sustained and program managers at all levels must be trained and educated to create the pool of knowledge and experience to conduct a successful program.[1] In the past, the growth and sustainment of key technical and management personnel in the submarine community was facilitated through numerous sequential design and acquisition programs. Personnel participated in one or more programs, gaining experience to be the leaders in future programs.

Due to increases in the operational lives of submarines and the constrained defense budgets faced by most nations, new submarine programs are occurring less frequently. There are now substantial gaps between new programs, providing fewer opportunities for personnel to gain the experience needed to manage complex processes and make informed decisions. Future managers of new programs may not have the benefit of learning from the challenges faced and the issues solved in past programs.

Recognizing the importance of past experience for successful program management, the Program Executive Officer for Submarines asked the RAND Corporation to develop a set of lessons learned from previous submarine programs that could help inform future program

[1] See Schank et al., 2005a; Schank et al., 2007.

managers. This volume describes the important lessons from the *Ohio*, *Seawolf*, and *Virginia* programs. Separate volumes in the series provide lessons from the United Kingdom and Australian submarine programs and a summary of the lessons learned from all three programs:

- MG-1128/1-NAVY, *Learning from Experience, Volume I: Lessons from the Submarine Programs of the United States, United Kingdom, and Australia*
- MG-1128/3-NAVY, *Learning from Experience, Volume III: Lessons from the United Kingdom's* Astute *Submarine Program*
- MG-1128/4-NAVY, *Learning from Experience, Volume IV: Lessons from Australia's* Collins *Submarine Program*.

This research was conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

For more information on the Acquisition and Technology Policy Center, see http://www.rand.org/nsrd/ndri/centers/atp.html or contact the director (contact information is provided on the web page).

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Summary

To design and construct nuclear-powered submarines, modern navies and shipbuilders need personnel and organizations that possess unique and specialized skills and expertise. These vessels are among the most complex systems that countries produce, and the technical personnel, designers, construction tradesmen, and program managers who work on them represent pools of knowledge that take years to collect and that cannot be replicated easily or quickly.

In years past, the pace of construction on replacement submarines was quick enough in most countries that key technical and management personnel in submarine programs were able both to work on a stream of successive submarines and to pass their knowledge on to personnel who followed in their footsteps. Individuals who participated in one program gained experience to be leaders or intellectual resources in following programs.

But two events have coalesced in recent years to complicate such transfers of knowledge: Defense budgets have become constrained, and the operational lives of submarines have lengthened as the vessels' production and maintenance procedures have benefited from continuous process improvements and as navies have changed how they operate the vessels. The result is that the pace at which submarines are being replaced is likely to slow, creating significant time gaps between successive programs and far fewer opportunities for veteran personnel to pass on their knowledge to succeeding generations of submarine workers and program managers.

Recognizing the importance of documenting and imparting experiences from past submarine programs, the U.S. Navy's Program

Executive Officer (PEO) for Submarines asked the RAND Corporation to develop a set of lessons learned from previous submarine programs that could help inform future program managers. The RAND project team focused on the *Ohio, Seawolf,* and *Virginia* programs; it derived lessons from previous reports[1] on the three programs and from numerous interviews that the team conducted with past submarine program managers and submarine personnel at the two shipyards that build U.S. nuclear submarines—General Dynamics Electric Boat in Groton, Connecticut, and Huntington Ingalls Industries–Newport News Shipbuilding, in Virginia.[2]

RAND's search for lessons also involved reviewing the history of U.S. nuclear submarines from the *Nautilus*, launched in 1955, through today's *Virginia* program; investigating how operational requirements were set for the *Ohio, Seawolf,* and *Virginia* classes; exploring the acquisition, contracting, design, and build processes that the three programs employed; and assessing the plans and activities surrounding integrated logistics support for those submarine classes.

Most of the lessons that RAND identified are managerial. The project team looked for instructive aspects of how the *Ohio*, *Seawolf,* and *Virginia* programs were managed, issues that affected management decisions, and the outcomes of those decisions. At times, it was difficult for the team to judge the "success" or the "failure" of program decisions. Views change during the conduct of a program and are based on the perspective of individuals. The important point is that the decisions were not necessarily "good" or "bad." Rather, they were or were not fully informed by knowledge of the risks and consequences.

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[1] For example, see Polmar and Moore, 2004; Schumacher, 1987, 1988a, and 1988b; and multiple reports from the United States Government Accountability Office (GAO). The full set of reports is listed in the Bibliography and spans research from 1980 through 2008.

[2] On March 31, 2011, Northrop Grumman spun off its shipbuilding division. The new organization is named Huntington Ingalls Industries. Since January 2008, Northrop Grumman Shipbuilding had been the name of the submarine shipbuilding facility at Newport News, Virginia. It was known as Northrop Grumman Newport News from 2001 until 2008, as Newport News Shipbuilding from 1996 until 2001, and as Newport News and Dry Dock Company before then. For simplicity's sake, we refer to the General Dynamics facility as Electric Boat (or EB) and to the Virginia shipbuilding facility as Newport News.

In some cases, the RAND team identified lessons that have not really been learned. In other cases, the team identified lessons that have been learned but forgotten (or ignored). Since cost is typically the metric for judging program success, the majority of the lessons focus on controlling program costs.

Three Submarine Programs in Perspective

The *Ohio* and *Seawolf* programs began in a period of heightened tensions between the United States and the Soviet Union, each pushing technology and force structures in an attempt to gain an advantage over the other. The end of the Cold War brought a change in operational focus, from countering the Soviet threat in waters around the globe to the world of terrorism and the need to operate in the littorals. This new operational environment is the one that the *Virginia* program has faced.

Available budgets for nuclear submarines mirrored this change in operational focus. The end of the Cold War brought a call for a "peace dividend" and a reduction in force structures. The Navy's force dropped from more than 100 submarines at the end of the *Los Angeles* program to approximately half that number today.[3] That drop in force structure coincided with turmoil in the industrial base as the large-procurement years of the *Los Angeles*–class submarines ended and the competition and rivalry between Electric Boat and Newport News evolved into a partnership on the *Virginia* program.[4]

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[3] The *Los Angeles* class had been conceived in the mid-1960s to operate with a carrier battle group to gain an attack position against Soviet submarines capable of achieving high speeds when submerged. It was designed when the U.S. Navy had a mid-ocean strategy and chose to avoid offensive operations in the Barents Sea and Sea of Okhotsk, where Soviet nuclear ballistic missile submarines might patrol.

[4] Both shipyards had large workforces at the start of the *Ohio* program. Workforce demands at both shipyards dropped significantly with the termination of the *Seawolf* program. Newport News was able to sustain a fairly large workforce to support new aircraft carrier construction and the mid-life reactor refuelings and major repair of in-service carriers. However, with submarines as its only product line, EB was forced to remake itself and significantly

All three submarine programs had tenuous beginnings. Each experienced cost overruns and schedule delays in the construction of its first-of-class submarine. The *Ohio* and *Virginia* programs made corrections, and both are viewed as generally successful. *Seawolf*, likely due to the changing threat and budgetary environment, was terminated before changes could be made to correct early missteps.

An overarching lesson from the three programs is the importance of program stability. Stability applies in many areas—funding consistency, a long-term build strategy, fixed operational requirements, program management, and an integrated partnership between the Navy and the shipbuilders. Program stability is not sufficient for program success, but it is certainly a necessary attribute that greatly contributes to the success of a program. The lessons that follow largely address ways to achieve program stability.

The *Ohio* Program

The *Ohio* class was an evolutionary enhancement of the Poseidon-carrying ballistic missile submarine. As the largest submarine then built in the United States, it carried 24 missiles. The ship had the same basic compartment layout as the Polaris/Poseidon–equipped submarines that preceded it. However, it had a larger missile capacity and hull diameter, which provided the option to design better living arrangements for the 165-man crew. Overall, its missile system and ship designs were generally conservative and avoided radical new technologies.

Although the Navy was concerned with various platform capability features, the *Ohio*-class submarine was ultimately designed to support an overall nuclear ballistic missile submarine (SSBN) operational availability. To that end, an integrated logistics system was designed along with the ship; two bases, at Kings Bay, Georgia, and Bangor, Washington, were optimized to support crew training and submarine logistics requirements. In addition, the *Ohio* class was designed with redundancies in its systems and with standardized equipment and installed spares, all of which helped ensure overall system reliability.

reduce its workforce in order to survive. Once heated rivals, the two shipyards now partner equally in the construction of the *Virginia*-class boats.

The *Ohio*-class program followed the same strategy as earlier nuclear submarine programs: minimizing technical risks by adopting the best technologies available at the time while pushing technology boundaries in only a few select areas. The program proceeded with few technical problems and is largely considered a success. It benefited from a robust industrial base and ample funding during a period of increasing defense spending intended to counter a growing Soviet threat.

The *Seawolf* Program

When the Soviets started to field improved submarines in the 1970s, the United States began to consider the design of the successor to the *Los Angeles* class.[5] Early concepts for an attack submarine focused on a number of smaller, less-expensive designs, including improving the capability of the *Los Angeles* class.[6] However, in 1981 as the new Reagan administration ushered in an era of expanded Cold War defense spending and a new maritime strategy, it soon became clear that the *Los Angeles*–class design margins were not adequate to absorb the upgrades that would be required.

In the new strategic and budgetary environment, the initial concept for a more affordable and less capable platform was set aside in favor of a more advanced platform that would both challenge the Soviet antisubmarine warfare (ASW) advantage and meet the needs of the new maritime strategy.[7]

The *Seawolf* program was initiated in 1982 with early concept development. A special naval study group was established to assess future threats and conduct technology feasibility studies. The *Seawolf*'s primary mission would be to hunt down and track Soviet ballistic missile submarines. The priorities in the development of the *Seawolf*'s

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[5] By the end of the 1970s, two decades of steady Soviet advances had resulted in the *Los Angeles* class losing some of its antisubmarine warfare advantage.

[6] Polmar and Moore, 2004, p. 172.

[7] The new maritime strategy served to underpin a 600-ship navy and the operational objectives of the fleet. The U.S. Navy wanted to counter the Soviet submarine fleet as far forward as possible, in the sea-denial and sea-control zones. At the outbreak of hostilities, U.S. submarines would now be expected to operate far forward both in the northwest Pacific and the northeast Atlantic. Hattendorf and Swartz, 2008, pp. 74–82.

operational requirements were increased stealth (acoustic silencing) and an improved combat system. Additional mission areas included anti-surface warfare, strike warfare, surveillance, and mine warfare.

These operational capabilities required significant advances in several technology areas. Reduced quieting, higher speeds, deeper diving depths, and larger payloads not only contributed to a large submarine but one that pushed current design limits. The *Seawolf* would require a new reactor, propulsion system, and combat system as well as the use of new steel. In many ways, the program deviated from one of the basic tenets of previous programs—limit the number of new technologies for a new class of submarines. But these multiple advances in technology were deemed necessary to meet the increasing capabilities of Soviet submarines.

The *Virginia* Program

The *Virginia*-class attack submarine was developed in the early 1990s as the successor to the *Los Angeles* and *Seawolf* classes. These classes had two things in common: Their roots were in the Cold War and, for different reasons, each had experienced unanticipated cost escalation during the construction programs. By the late 1980s, the *Los Angeles* class was in full production while the *Seawolf* program was beginning construction.

With the end of the Cold War and with growing concerns over the cost of nuclear submarines, the Navy and the shipbuilders took a different approach with the *Virginia* program. They realized that designing and building a lower-cost submarine that responded to the new threat environment was imperative for the survival of the submarine program and, to a large extent, to the nuclear submarine industrial base. Having learned from the *Seawolf* program and remembering the lessons from earlier programs, the *Virginia* program sought to reduce risks by using the best technologies available while constraining the development of new technologies.

Some of the *Virginia* lessons mirror those of the *Ohio* and *Seawolf*: Use a single design/build organization; have an appropriate level of design complete before construction starts; obtain congressional and

Department of Defense (DoD) support for the program; and maximize the degree of modular construction to reduce build costs.

Top-Level Strategic Lessons from the Three Programs

Top-level strategic lessons are global in nature and span all programs that design and build new platforms or support the U.S. Navy submarine force. They are appropriate for the PEO for Submarines and for senior U.S. Navy management. These strategic lessons address the overall management of the nuclear submarine force and of the industrial base and include the following:

- *Have experienced technical and programmatic leadership at the helm and develop strategies to grow knowledgeable and experienced managerial, oversight, and technical support personnel.* The Navy must continue to grow the right levels of expertise in the right people, sending them to various operations- and acquisition-related positions as well as providing appropriate education in the academic community. It is critical that the Navy identify the most promising junior officers for future management positions and provide them with learning experiences. Equally important is the civilian leadership in the various Navy technical organizations and laboratories and in the private sector.
- *Take a long-term, strategic view of the submarine force and the industrial base.* A new submarine development program produces more than a strategic military asset; it also contributes to domestic economic goals and is one part of a long-range operational and industrial base strategy. Technologies change, new capabilities are needed, and new threats emerge and evolve. These future evolutions require maintaining a technology/capability edge and updating existing platforms with new technologies and new capa-

bilities.[8] The technical community[9] and the industrial base must be sustained so they can provide the required capabilities when needed.

Lessons in Supporting and Managing the Three Programs

Future program managers must "manage" from several perspectives. They must interact with shipyards and vendors. They must understand technologies and how they successfully support the program. And they have to manage the expectations of higher-level organizations (the PEO, senior Navy leadership, and Congress). A strong management team is important for program success. Important lessons here include the following:

- *Ensure that the program is adequately supported by the Navy, the government, the scientific community, and the public.* Support must be both external to the program and internal within the Navy and submarine community. Political support is most important for the advancement of a new acquisition program. Support also must come from within the Navy.
- *Ensure that the program is open and transparent*. Full disclosure during the program is necessary to obtain the support of the Office of the Secretary of Defense (OSD), Congress, industry, and the public. In this regard, a good media management program is necessary. Bad press greatly and negatively affects the program. Effective communications must be proactive, not reactive, when briefing the Navy leadership, OSD, Congress, the media, academia, and others.

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8 The improved *Los Angeles* class, the conversion of the *Ohio*-class SSBNs to nuclear cruise missile submarines (SSGNs), and the construction of the USS *Jimmy Carter* are three examples of how original designs were modified for new missions and capabilities. At some point, however, new classes of submarines must be designed and constructed.

9 This includes the Navy's engineering directorates and the laboratories, test centers, and centers of excellence that support nuclear submarines.

- *Involve appropriate organizations, commands, and personnel from the beginning.* The program and the Navy must be informed customers supported by adequate technical, operational, and management expertise.[10]

Lessons from the Three Programs in Setting Operational Requirements

Decisions made very early regarding the desired operational performance of the new submarine influence the technology risk for the program and its likelihood of success. The operational requirements for the platform are translated to performance specifications that lead to technology choices to achieve the desired performance. The operational requirements, especially the desired operational availability, also affect integrated logistics support (ILS) planning. Important lessons here include the following:

- *Clearly analyze and state system requirements as a mix of key performance requirements and technical standards.* The requirements set during the contract should remain as fixed as possible for the extent of the design period. The Navy should control to the degree possible any requirements growth except where absolutely necessary. Operational requirements and technologies will change over time, resulting in major modifications during a submarine's operational life. When setting the requirements for different submarine systems, programs must understand the current and

[10] In addition to the technical community, the program office must involve operators, builders, and maintainers from the beginning of the program. The program manager should plan on spending the time necessary to ensure that the program philosophy and underlying principles (cost control, low technology risk, for example) are clear to all participants and emplaced at all levels. In addition, the program manager should be empowered with required decisionmaking authority (e.g., change control).

emerging technologies in those systems, how requirements might change in the future, and the trade-offs between costs and risks.[11]

- *Understand the current state of technology as it applies to the program and how the platform's operational requirements affect technology risks and costs.* Desired operational performance will drive the characteristics of the platform and the technologies needed to achieve the performance goals. Program managers must be supported by a technical community that completely understands the technologies that are important to the program, where they exist, and which ones must be significantly advanced. Relying too heavily on significant advances in technology will lead to risks in achieving the desired operational capabilities.[12]
- *Understand that operational requirements must also specify how to test for the achievement of that requirement*. Although it is often difficult to plan tests early in a program, it is necessary to ensure all parties agree on the processes to measure how the performance of the platform meets operational capability objectives.

Lessons from the Three Programs in Establishing an Acquisition and Contracting Environment

Establishing an open and fair acquisition and contract environment is another important aspect of any program. Good decisions here—the organizations that will be involved in designing and building the

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[11] The *Ohio* program faced such a trade-off when setting the number and size of the missile tubes. More and bigger tubes would result in a larger submarine. Working closely with the Strategic Systems Program Office, the *Ohio* program set a requirement for a missile tube with a larger diameter than needed for the C4 missile. This decision resulted in a relatively smooth transition as the last eight submarines in the *Ohio* class were specifically built to carry the D5 missile. A similar decision during the *Seawolf* program led to a less-favorable outcome. The *Seawolf* design included eight torpedo tubes each 26.5 inches in diameter versus the 21-inch tubes on previous classes. These larger tubes, in combination with a larger weapon load, led to a much larger pressure hull than on previous classes of attack submarines.

[12] The developmental platform and the developmental combat system in the *Seawolf* led to a high degree of risk. Backing off requirements slightly, especially with the combat system, could have significantly reduced those risks.

new submarine, the type of contract, the specifics within the contract (including incentives), the decisionmaking process to employ when issues arise, and the payment schedule—will resonate throughout the life of the program. Key lessons for establishing an effective acquisition and contracting environment include the following:

- *Consider a single integrated design/construction contract with the prime.* Having a single firm complete the detailed design and build of the submarine helps to integrate the two processes and reduces confusion and misinterpretations.[13] Even with a single contract for design and build of the first-of-class, the lead ship should be priced only when the detailed design is sufficiently complete for both the shipbuilder and the Navy to have enough knowledge to estimate realistic costs.
- *Use a contract structure that has provisions to handle program risks.* While the Navy can try to place all risk on a contractor through use of a fixed-price contract, the Navy ultimately holds all program risk. It is far better to structure a contract that holds the contractor responsible for risks under its control (labor rates, productivity, materiel costs, etc.) and holds the Navy responsible for risks beyond the contractor's control (inflation, changing requirements, changes in law, and so forth).[14]

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[13] The *Ohio* program had one organization, EB, design and build the submarines, but entered into separate contracts with different EB divisions to design and build the first-of-class. This led to schedule delays and cost growth to reconcile differences between the different contracts. The *Seawolf* program had the shipbuilders each design portions of the ship with competition for building the first-of-class. Again, there were significant problems with this approach. The *Virginia* program involves a single design/build prime contractor, with Newport News serving as a major subcontractor. This arrangement, plus other initiatives, has resulted in a largely successful program.

[14] The lead ship contracts for *Ohio* and *Seawolf* were both fixed-price, incentive-type contracts. Both had escalation provisions that covered the effects of inflation up to ceiling price and up to the contract delivery date without penalty. Both had substantially larger spreads from target cost to ceiling price than early *Los Angeles*–class contracts possessed. The *Virginia* program took a different approach. Rather than providing the detailed design drawings as government furnished information to the construction shipyard, *Virginia* added cost-plus-incentive-fee construction line items for the lead ship to the original cost-plus design contract.

- *Develop a timely decisionmaking process to minimize and manage changes.* Changes invariably occur during any program. They may crop up in the desired performance of the platform, in the systems and equipment used to achieve performance, in the schedule, or in the responsibilities of the organizations involved in designing, building, and testing the platform. Changes may affect cost, schedule, or capability. Management structures must be in place to deal with any of the contract changes that are proposed during the program.
- *Establish an agreed-upon tracking mechanism and payment schedule*. It is important that a program have an effective system for tracking progress and costs that involves all appropriate organizations—the Navy, the program office, the SUPSHIP, and the contractor. This system must thoroughly address all the appropriate issues and their impact on cost, schedule, and performance. The payment schedule should be tied to clearly defined and meaningful milestones.

Lessons in Designing and Building the Three Programs' Submarines

It is important that all the right organizations—designers, builders, operators, maintainers, and the technical community—are involved throughout a program, so that they understand how operational requirements affect design and construction and can plan for the appropriate testing of the systems and platform to ensure that requirements are met. To some degree, lessons for the design and build process overlap lessons that emerged from programs' earlier stages:

- *Involve builders, maintainers, operators, and the technical community in the design process.* Design/build should go further than merely involving builders in the design process. It is important to think of the design team as a collaboration of submarine draftsmen and design engineers with inputs from those who must build to the design, operate the submarine, and maintain it. This col-

laboration should extend throughout the duration of the design program. However, throughout the process, it is important to keep in mind that the cost-effectiveness of the submarine's post-delivery or ILS period is the true design and construction target.
- *Design for removal and replacement of equipment*. Adequate access paths and removal hatches should be included in the design to facilitate removing and replacing damaged or obsolete equipment. For command, control, communications, computing, and intelligence (C4I) equipment, modularity and interoperability should be incorporated into the design.
- *Complete the majority of the design drawings before the start of construction.* It is far better to delay construction to ensure the design is largely complete rather than risk the costly rework and changes typically resulting from an immature design. A good rule of thumb is to have the arrangements 100 percent complete and the overall design approximately 80 percent or more complete when construction begins.
- *Conduct a thorough and adequate test program*. Testing should involve the design and build organization(s) as well as the technical community and the Navy.

Lessons from the Three Programs in Planning for Integrated Logistics Support

Operating and supporting new submarines after they enter service account for the vast majority of their total ownership costs. Therefore, it is imperative to establish an ILS plan for the new submarines. Important lessons here include the following:

- *Establish a strategic plan for ILS during the design phase.* Such a plan must be put in place early in the program. Personnel from organizations responsible for maintaining the submarine should be involved in the design process. Additionally, the submarine's concept of operations must recognize that the vessel will require time for preventive and corrective maintenance and for equipment modernizations.

- *Establish a planning-yard function and develop a maintenance and reliability database*. A planning-yard function to track maintenance and establish future workloads is important to ensure the right maintenance is done at the right times.
- *Plan for crew training and transition of the fleet.* The ILS plan must also include the when, where, and who for training activities, and the transition of personnel to the new submarine class. Typically, the crew assigned to a submarine during construction validates operating and casualty procedures and instructions, functions as a system and equipment validation organization for the Navy, and serves as the ship's trials and test operator.

Acknowledgments

This research was initiated and supported by RADM William Hilarides, then the PEO for Submarines. RADM David Johnson, the current PEO for Submarines, supported the research through its final phases. We greatly appreciate their support and guidance during the study. Ann Birney, Director, International Programs, identified key individuals to interview and facilitated those meetings. In addition, many other people with knowledge and experience of U.S. submarines shared their time and knowledge with us. RADM (Ret) Phil Davis and Paul DeLuca of RAND provided useful comments on an earlier draft that helped strengthen the overall document. At RAND, Deborah Peetz provided support in identifying and obtaining reports and background information on the various submarine programs.

Of course, any errors of omission or commission in the document are the sole responsibility of the authors.

Abbreviations

ABM	antiballistic missile
AEC	Atomic Energy Commission
APDM	Amended Program Decision Memorandum
ASW	antisubmarine warfare
BUR	Bottom-Up Review
C4I	command, control, communications, computing, and intelligence
CAD	computer-assisted design
CFE	contractor-furnished equipment
CNO	Chief of Naval Operations
COEA	cost and operational effectiveness analysis
CPI	cost performance index
DoD	Department of Defense
EB	Electric Boat
EOA	early operational assessment
EVMS	earned value management system
FBM	fleet ballistic missile
FY	fiscal year

GAO	Government Accountability Office
GFE	government-furnished equipment
GFI	government-furnished information
ILS	integrated logistics support
IMS	integrated master schedule
IPPD	Integrated Product and Process Development
MAP	manufacturing assembly plan
MAT	major area team
NAVSEA	Naval Sea Systems Command
ND	nondeviation
NSSN	new attack submarine
OPTEVFOR	Operational Test and Evaluation Force
ORD	Operational Requirements Document
PDM	Program Decision Memorandum
PEO	Program Executive Officer
PSA	post-shakedown availability
SALT	Strategic Arms Limitations Treaty
SASC	Senate Armed Services Committee
SECDEF	Secretary of Defense
SECNAV	Secretary of the Navy
SIT	system integration team
SLBM	submarine-launched ballistic missile
SPI	schedule performance index
SSBN	nuclear ballistic missile submarine

SSGN	nuclear cruise missile submarine
SSN	nuclear attack submarine
SSPO	Strategic Systems Program Office
SUBACS	submarine advanced combat system
SUBCOM	Submarine Computer Oriented Management
SUBSAFE	submarine safety
SUPSHIP	Supervisor of Shipbuilding
TRIPER	Trident Planned Equipment Repair
ULMS	undersea long-range missile system

CHAPTER ONE

Introduction

Lessons from past experiences are an important tool for preparing managers to conduct future programs successfully. This is especially true for the management of complex military programs governed by various rules, regulations, procedures, and relationships not typically found in commercial projects. In the past, frequent new programs afforded junior-level managers the opportunity to gain experience, develop insights, and prepare for more senior management roles in future programs. However, the longer operational lives of current naval platforms and the pressures of constrained defense budgets have resulted in longer gaps between new programs, and new program managers often do not have the benefits of experiences gained on previous programs. In this environment, it is important that lessons from previous programs, both good and bad, be captured and provided to future program managers.

Recognizing the need to document the lessons from past programs to provide insights for future program managers, the submarine organizations of the United States, the United Kingdom, and Australia asked the RAND Corporation to codify the lessons from past submarine design and acquisition programs. This volume presents lessons learned from the U.S. *Ohio*, *Seawolf*, and *Virginia* submarine programs.

The document organizes the various lessons identified in previous reports on the *Ohio*, *Seawolf*, and *Virginia* programs[1] as well as during numerous interviews with past submarine program managers and submarine personnel at the two shipyards that build U.S. nuclear submarines—General Dynamics Electric Boat in Groton, Connecticut, and Huntington Ingalls Industries–Newport News Shipbuilding, in Virginia.[2] We were particularly interested in

- how political, budget, and operational environments influenced decisions made during the program
- how operational requirements guided the design efforts and how those requirements related to the technologies available at the time
- what contracting and acquisition processes were used during the program
- how the private-sector industrial base that designs, builds, and maintains submarines and their systems changed over the more than 60-year history of U.S. nuclear submarines
- how the Navy and the shipbuilding industrial base interacted
- how integrated logistics support (ILS) plans were developed during the design and construction of the submarines to support the new submarines when they entered service
- how other issues, both internal to the program and external, influenced decisions and outcomes.

The lessons we strive to identify are managerial in nature, not technical. We do not focus, for example, on why a specific valve or pump was chosen, but rather on how the program was managed, the

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[1] For example, see Polmar and Moore, 2004; Schumacher, 1987, 1988a, 1998b, and multiple reports from the U.S. Government Accountability Office (GAO). The full set of reports is listed in the Bibliography and span research from 1980 through 2008.

[2] On March 31, 2011, Northrop Grumman spun off its shipbuilding division. The new organization is named Huntington Ingalls Industries. Since January 2008, Northrop Grumman Shipbuilding had been the name of the submarine shipbuilding facility at Newport News, Virginia. It was known as Northrop Grumman Newport News from 2001 until 2008, as Newport News Shipbuilding from 1996 until 2001, and as Newport News and Dry Dock Company before then. For simplicity's sake, we refer to the General Dynamics facility as Electric Boat (or EB) and to the Virginia shipbuilding facility as Newport News.

issues that affected management decisions, and the outcome of those decisions.

It is often very difficult to judge the "success" of a specific program; success can be measured in performance, cost, or schedule terms. One person's view of how successful a program was can differ greatly from the views of others. It is even more difficult to identify specific actions or decisions that contributed to success or non-success; many factors interact throughout the conduct of a new program.

Because we seek to identify for future program managers those key aspects of a program that will help guide them in bringing a program to a successful conclusion, we discuss the lessons learned from each program in the historical context of that program.

Organization of This Document

Chapter Two provides a brief background of U.S. nuclear submarines from the USS *Nautilus* up to the start of the *Ohio* program. It also presents some basic guidelines developed by the submarine community during that early period. Chapters Three, Four, and Five describe the *Ohio*, *Seawolf*, and *Virginia* programs, respectively. Each chapter provides background for the program and then describes how requirements were set, what acquisition and contracting strategies were used for the program, the design and construction of the submarines, and what may have contributed to cost and schedule delays. Chapter Six summarizes the lessons learned from the three programs. An appendix shows the major milestones in the three programs.

CHAPTER TWO

U.S. Nuclear Submarines Up to *Ohio*

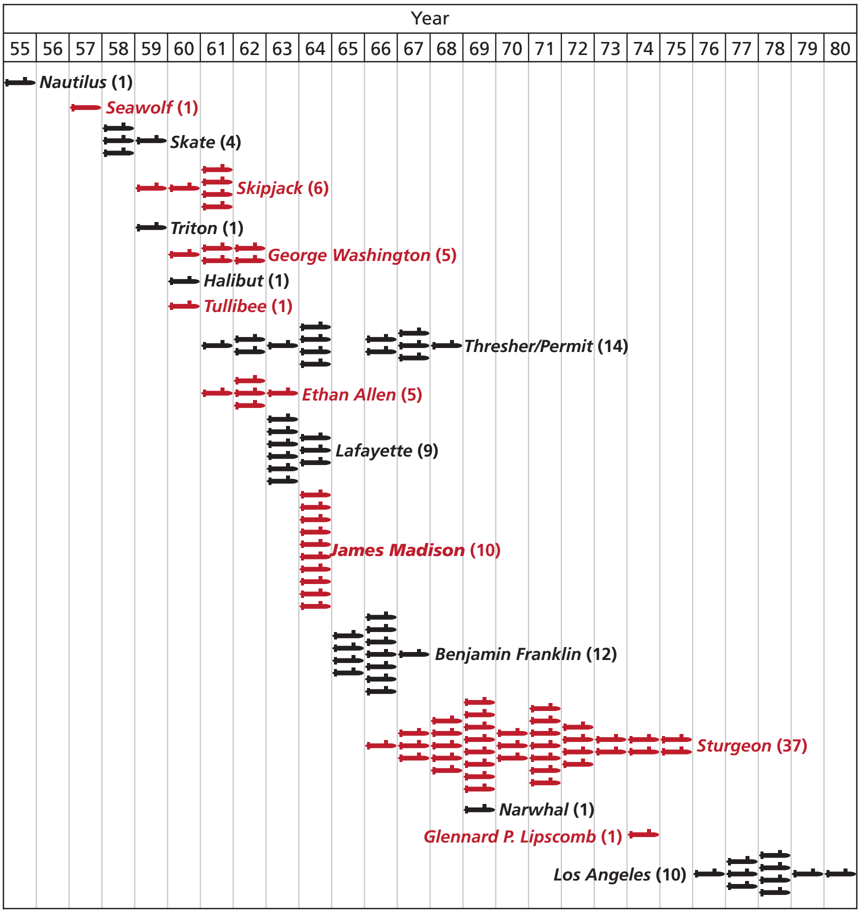
Historical context is important when we discuss the lessons learned from the United States' *Ohio, Seawolf,* and *Virginia* nuclear submarine programs. All three came during or just after the peak in U.S. nuclear submarine design and construction. However, the period before the start of the *Ohio* program provides a good insight into the basic tenets of program management developed earlier by the nuclear submarine community.

Figure 2.1 shows the various classes of nuclear submarines developed between 1955 and 1980. The numbers in parentheses indicate the number of submarines in each class. The figure shows the first ten in a class of more than 60 *Los Angeles*–class submarines.

From the time of the USS *Nautilus* through the beginning of the *Los Angeles*–class program, the Navy maintained a significant in-house core competency in submarine design that was regularly exercised and deeply involved in the initial designs of successive classes of U.S. submarines. By the beginning of the 1960s, nuclear submarine construction was taking place in six shipyards nationwide. In addition, the Navy maintained a separate engineering core competency, inasmuch as it assumed the role of both the design authority and the technical authority during ship design and construction.[1] These design and

[1] The designer's role was to design a submarine to meet the operational requirement. That is, to achieve a certain level of quieting, to house a specific propulsion system which met speed requirements, to reach a certain depth safely, to carry and launch the specified weapons, to meet shock requirements, and so forth. The *design authority's* role is to forward to the designer the design specifications or rules. These are usually based on the submarine concept

Figure 2.1
Nuclear Submarines Commissioned, by Class (1955 to 1980)



NOTE: For clarity, we alternated colors between the various classes.
RAND *MG1128/2-2.1*

selected from the concept studies that preceded the design effort. The design authority must be consulted and approve any proposed changes to the design specifications. In contrast, the *technical authority* is the subject matter expert in various areas such as the submarine hull, mechanical and electrical engineering, submarine safety and ship design and engineering. The technical authority is responsible for establishing technical standards in each area and for evaluating the risk when a design does not conform with technical standards, which might occur during the design and construction processes. To be effective, the design and technical authority roles required skilled and experienced staff with predominantly technical and engineering skill sets.

engineering core competencies supported small technical staffs in the ship acquisition directorates and initiated the submarine procurement process with concept and feasibility studies. The concept, feasibility, and preliminary design studies all accommodated input from the fleet on operational requirements.[2] These teams led relatively discrete low-cost decision processes to develop preliminary designs in which all of the major technical issues were identified and provided with appropriate design margins and development programs.

The Navy's design process led to the contract design, which included ship specifications, arrangement drawings, and a weight estimate, all of which controlled the hull form. These outputs would be used to obtain either competitive bids or sole source estimates from construction shipyards. The lead building yard for a class of ships would then prepare working drawings, purchase orders, and a myriad of other detailed documentation necessary to build the ship. Shipyards that built the follow-on ships in the class could buy this detailed documentation for the cost of reproduction to save the Navy the cost of duplicating this detailed work. Both the lead and follow yards could deviate from these detailed working drawings as long as the ship met specification requirements. For *Nautilus*, this paradigm changed slightly. The detailed drawings for the reactor plant were prepared under a separate contract provided to the shipbuilder by the government; they were to be followed without deviation. These drawings became known as non-deviation (ND) drawings.

Over time, the number of ND drawings increased. After the *Thresher* sinking in 1963, the Navy instituted the SUBSAFE program, which, among other requirements, provided ND drawings for all systems and boundaries subjected to submerged seawater pressure. By the time the *Los Angeles* class was designed, the Navy had contracted for an entire set of detailed working drawings to be provided to the building yards; the government was liable if the ND drawings prevented the

[2] The traditional ship or submarine design process went through a number of steps, each adding more detail to the design. Concept, feasibility, and preliminary design were specific steps in this sequential process. See Schank et al., 2005 and 2007, for definitions of these design steps. The *Virginia* program adopted a parallel design/build process that eliminated some of the delays in a design effort inherent in the sequential process.

ship from meeting specifications. However, the shipbuilder was still responsible for meeting specifications even if it followed government-furnished drawings that were not ND. This provision led to numerous contract disputes.

Although *Nautilus* was a revolutionary ship because of her propulsion plant, in most other respects, she was evolutionary at best. Her hull form resembled that of World War II submarines, which spent most of their time on the surface. The second nuclear-propelled submarine (*Seawolf*) was similar, except that she went to sea with a liquid metal–cooled reactor plant. It was not until *Skipjack*, the seventh nuclear submarine, that designers truly took advantage of nuclear power's ability to operate independent of air to design a hull form optimized for underwater performance. Most other attack submarines until *Los Angeles* and all 41 Polaris nuclear ballistic missile submarines (SSBNs)[3] used the reactor plant designed for *Skipjack*. The exceptions were several one-ship classes, such as *Tullibee, Triton, Narwhal,* and *Glenard P. Lipscomb*, which explored either alternate propulsion plant concepts, such as new reactors, or turbine electric drive.

Historical Lessons in Submarine Acquisition

Our interviews suggested that during these early years the submarine force carried several basic lessons from design to design. Among the important ones were the following:

Controlling risk when introducing new designs is important. This was done in two ways. First, the introduction of new technologies in a class was limited. Generally, only one major new technology would be introduced in any major ship design change or new class. The ship would either get a new propulsion plant upgrade or a new combat system, but seldom both. Further, prototyping was considered an

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[3] A Polaris SSBN was any variety of SSBN equipped with Polaris missiles, not a distinct class of SSBN.

effective means of risk reduction.[4] This approach was routinely used to limit risk in combat system upgrades. Progressive combat systems were proven with at-sea or on-land prototypes before being introduced into new-construction ships. This was true, for example, when the fleet transitioned from analog to digital fire control systems, to spherical sonar array systems, and to the *Albacore* hull form.

Submarine design margins must be robust, since they are continually eroded during a particular submarine's lifetime. The submarine design is initially constrained by internal volume. Because national security strategies and concepts of operations would likely change during the lifetime of a particular design, feasibility studies examined and established sufficient design margins to accommodate changes in strategy or concepts of operation. The design would provide the flexibility and adaptability to accommodate future missions, weapons, and operational concepts.

Submarine design and construction must be a "systems effort." To be successful, the broad nuclear submarine "system" would be purposefully cultivated. That is, a requirements and concept evaluation process was needed that was supported by research and development and that fed a design and construction industrial base coupled to a ready support infrastructure and a trained and ready crew. To be successful, both submarine design and class upgrade programs relied on maintaining a competent core engineering capability. A proven and qualified vendor base was important for success.[5]

Continuous new design work was important to maintain the efficacy of both the Navy nuclear submarine design and engineering talent base. With the transition to fewer classes and types of submarines in the 1960s, the Navy began to witness the loss of experienced subma-

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[4] For example, the diesel-powered USS *Albacore* (a research vessel) was a prototype for the hull form used on *Skipjack,* and the spherical sonar array was prototyped on *Tullibee* before being included on *Permit*.

[5] Groups that provided technical support to the "system" were the naval shipyards that had built many of the early submarines; Navy laboratory organizations at Carderock, Dalghren, and Newport; and universities such as Columbia, Penn State, Massachusetts Institute of Technology, and Johns Hopkins (Applied Physics Laboratory). Here the Navy nurtured and received first-rate production, maintenance, scientific, and academic input.

rine designers and of its engineering talent. The immediate and obvious way to compensate for this was to underwrite this capability in the commercial sector and in the shipbuilding industry. Thus, by the time both *Ohio* and *Seawolf* were ready to be designed, the government design option no longer existed. However, adequate engineering talent remained within the government to perform the oversight roles of *design* and *technical* authorities.

Continuous construction work was important to advance construction techniques and to accommodate new materials and systems. The industrial base that built the submarines continuously adapted the manufacturing processes to respond to new materials and new systems that were incorporated into successive classes. New, higher-strength steels were tested and adopted and the integration and testing of new electronic and sensor systems became more complex. Most important, the Navy and private-sector companies developed and implemented exacting specifications for nuclear and submarine safety that resulted in a highly disciplined and uniquely skilled culture.

These high-level lessons were etched in the history of the programs that preceded the *Ohio*, *Seawolf,* and *Virginia* programs, which we review in the following chapters.

CHAPTER THREE

Ohio Case Study

As the *Los Angeles* program was reaching full production, the vessels in the original SSBN fleet were nearing the end of their operational lives. The Soviet Union posed an increasing threat, and strategic nuclear deterrence was accorded high priority. The nuclear propulsion industrial base, due to submarine production and new aircraft carrier construction, was healthy although centered on only two shipyards—EB and Newport News. This environment gave rise to the *Ohio* program, the first case study we examine for lessons learned.

Background

The decade of the 1950s saw the steady buildup of Soviet strategic forces and the launch of the Soviet Sputnik satellite. Counter to prior notions, Project Budapest suggested that just a few hundred warheads would be needed to deter the Soviets from a first strike.[1] More nuclear attack capability would add little to the destruction.[2] This implied that the Navy could provide a valuable strategic deterrent, so efforts began on the development of a submarine to launch nuclear ballistic missiles.

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1 See Rosenberg, 1984. Project Budapest was a joint Army-Navy study of the fallout and radiation implications of the Strategic Air Command's war plan.

2 Friedman, 1994, p. 195.

In order to acquire the SSBN system, the Department of the Navy created the Special Projects Office.[3] This office was given full responsibility for the SSBN program and the authority to design, develop, produce and support the system in the shortest time possible.[4]

The SSBN program pursued four major areas:

- developing a ballistic missile, using solid rocket fuel
- reducing the size and weight of nuclear warheads
- identifying breakthroughs for the fire control system in guidance and navigation technologies
- designing a nuclear submarine launch platform.

The resulting Polaris weapon system was designed and its submarine initially went to sea in late 1960 with a rotational two-crew operating concept. This concept increased the amount of time the submarine could be at sea (and consequently increased the time Polaris missiles were within target range). Polaris-equipped submarines were designed with adequate growth margins for a future upgraded missile system and robust communications and navigation suites.

Over the next decade, the Special Projects Office oversaw the development of five classes of ballistic missile submarines,[5] and by 1967 a total of 41 Polaris- and Poseidon-equipped submarines were at sea, as shown in Table 3.1. All but the first ten were eventually converted to carry and launch higher capability missiles.

The development of the U.S. SSBN had several consequences, among them the beginning of a long-term Soviet strategic antisub-

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[3] The Special Projects Office was renamed the Strategic Systems Projects Office in July 1968 and later the Strategic Systems Program Office (SSPO).

[4] Because of its priority, the Chief of Naval Operations, Arleigh Burke, wanted to ensure that the program had a "vertical organization" separate from the existing technical bureaus which reported to him. He was supported by the Secretary of the Navy. See Polmar and Moore, 2004, p. 119.

[5] The first five classes of SSBNs were the *George Washington* class (5 boats), the *Ethan Allen* class (5 boats), the *Lafayette* class (9 boats), the *James Madison* class (10 boats), and the *Benjamin Franklin* class (12 boats).

Table 3.1
U.S. Fleet Ballistic Missile Submarines (cumulative totals in each year)

Year	Launched	Commissioned	Deployable	SLBMs Deployed
1959	4	1	0	0
1960	6	3	2	32
1961	9	6	5	80
1962	15	9	9	144
1963	27	16	10	160
1964	32	29	20	320
1965	39	33	29	464
1966	41	40	37	592
1967	41	41	41	656

SOURCE: Strategic Systems Project Office, 1983, pp. 16–17.

marine warfare (ASW) effort.[6] Another consequence was an effort to develop antiballistic missile (ABM) systems by both the United States and the Soviet Union. As multiple reentry vehicles and decoys were developed in the face of the Soviet ABM systems, the net effect was to move about half of U.S. nuclear warheads to sea by the early 1970s.[7]

By 1966, concern arose over the development of a new Soviet ABM system and the potential vulnerability of the Polaris system to Soviet strategic ASW progress. In addition, the Office of the U.S. Secretary of Defense was concerned about the lack of coordination among various U.S. strategic programs being developed with a view to countering the Soviet ABM systems.

Because of this concern, the Institute for Defense Analyses initiated a study known as the STRAT-X study, "to characterize alternatives to counter the possible Soviet ABM deployment and the Soviet potential for reducing the U.S. assured destruction force effectiveness

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6 Polmar and Moore, p. 184.

7 The majority of the nuclear warhead tonnage remained on land-based missiles and bombers, however.

during the 1970s."[8] Among the alternatives that the study evaluated, the Navy undersea long-range missile system (ULMS) was the preferred candidate and the only one developed. From its inception, the ULMS was considered by the Navy to be the successor to the Polaris submarine system, from which the Navy originally expected a 20-year lifetime.

The STRAT-X study recognized the need for a more capable fleet ballistic missile and a modernized delivery platform to account for the Soviet Union's increasing ASW capability and for the aging U.S. SSBN fleet. Also, in 1969 the ongoing Strategic Arms Limitations Talks (SALT) created an independent impetus for the U.S. administration to have a credible new submarine program under way to use as leverage when negotiating with the Soviet Union.[9] These talks influenced the perceived need for an advanced fleet ballistic missile (FBM) system and put immediate pressure on the Navy's design and acquisition decision processes.

By 1971, the Secretary of Defense had approved a plan to develop ULMS while preserving the option for an "advanced Poseidon" missile that was proposed to replace the existing Poseidon missile. The new missile would be larger and have a longer range and greater capabilities. Like the Polaris submarines, design features and requirements for the associated submarine platform were primarily influenced by the strategic mission needs and by the projected features of the new missile system.

The fiscal year 1974 (FY74) appropriations act provided the Navy funding for the first of the new class of SSBN submarine, called the *Ohio* class. Initial estimates proposed a fleet of ten submarines, all based in Bangor, Washington. Soon that number rose to 11. By 1977, fleet size would be 14; the number kept rising incrementally until 1988 when 21 ships were budgeted. Ultimately, SSBN 743, the 18th ship, would be the last and final *Ohio*-class submarine. The first eight submarines of the class were initially equipped with Trident I C4 missiles. All would eventually be upgraded with the Trident II D5 missile.

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8 Spinardi, 1994.

9 Schumacher, 1987.

Setting the Requirements

The STRAT-X study proposed a slow, quiet, austere new submarine that did not necessarily have deep diving capabilities. Its slow speed and quiet signature would reinforce its strong survivability characteristics and lower the probability that it would be detected. Stealth was a higher priority than speed, and the study concluded that its top speed should be no higher than 13 knots. Additionally, the study members suggested that the new missile carried by the platform would have a range of around 6,000 nautical miles (nm) and that each boat would have no fewer than 16 missile tubes. The submarine would have a central watch station that would require a smaller crew, thereby placing fewer demands on life support systems than those on previous submarines. Finally, it would employ new modular construction to build the hull and interior systems in sections, which would increase construction efficiency and hopefully shorten the production schedule.[10]

Vice Admiral Hyman Rickover, head of the Navy's Nuclear Propulsion Directorate, argued that the new submarine needed to reach a speed of at least 24 knots to keep up with Soviet submarines. Although Soviet submarines at this time could reach speeds of up to 30 knots, Rickover asserted that the submarine's performance would be hindered above 24 knots. Twenty knots was the maximum speed at which active sonar could still function effectively.[11] Rear Admiral Levering Smith, head of the Navy's Strategic Systems Projects Office, was a big advocate of low risks and of relying on existing technology for the hull design. However, he was also a proponent of larger missiles to attain greater ranges, which in turn would require larger missile tubes than on previous classes. In 1970, Rickover and Smith reached an agreement that the new submarine would have missile tubes 3.5 times larger in volume than the Poseidon tubes, achieve speeds of 26 to 27 knots on twin reactors, have a 50-foot hull, and displace 30,000 tons. These specifications were ultimately rejected by the Deputy Secretary of Defense.

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[10] Schumacher, 1988a.

[11] Schumacher, 1988a, p. 8.

Under Admiral Elmo Zumwalt, then–Chief of Naval Operations, the new project was renamed "Super 640"[12] and new specifications were proposed. The proposed platform was similar to the original requirements set by STRAT-X but would only have one reactor and a smaller hull than originally anticipated. The most significant change from the STRAT-X was a 10 percent larger missile tube size. In April 1971, EB was awarded a $35 million contract to start a submarine design that would adhere to these requirements.

The *Ohio* class was an evolutionary enhancement of the Poseidon missile submarines. As the largest submarine ever built in the United States, it would carry 24 ballistic missiles. As on submarines equipped with the Poseidon missiles, these missiles would be internal to the ship in two rows aft of the sail. Quieting would be a predominant design feature. A quiet new natural circulation reactor (S8G) would power the submarine to provide enough speed for adequate underwater maneuverability. Overall, however, its missile system and ship designs were generally conservative, and radical new technologies were avoided.[13]

The ship had the same basic compartment layout as the Polaris/Poseidon–equipped submarines. The larger missile capacity and hull diameter allowed the option to design better living arrangements for the 165-man crew.

Although the Navy was concerned with various platform capability features, in the end the *Ohio*-class submarine was designed to support an overall SSBN operational availability. In support of this, SSBN ILS was designed along with the ship. Two bases, at Kings Bay, Washington, and Bangor, Georgia, were optimized to support the crew training and submarine logistics requirements with academic buildings, drydocks, missile loading facilities, and maintenance capabilities. The Trident Planned Equipment Repair (TRIPER) program would schedule and remove equipment from submarines returning from patrol for repair and refurbishment ashore. This equipment would

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[12] The USS *Benjamin Franklin*, SSBN 640, was the last of the five classes that made up the first 41 SSBNs.

[13] For example, the nuclear reactor technology had already been proven at sea on board USS *Narwhal*.

be replaced with refurbished equipment during regularly scheduled upkeep. While ships were at sea, the TRIPER program would perform maintenance on the rotatable pool of equipment.[14] In addition, the *Ohio* class was designed with redundancies in its systems as well as standardized equipment and installed spares, all of which helped ensure overall system reliability. Although the SSBN ILS system and the redundancies built into the submarines were expensive, they helped increase the operational availability of the submarines and resulted in the need for fewer submarines in the class to meet desired deployed requirements.

The submarine's larger volume provided for an ample area to maintain equipment. Paths to install and remove major equipment (large pumps, valves, selected equipment) and handling systems were designed into the ship. Also designed into the platform were oversize equipment removal hatches and rigging pad eyes to facilitate planned upkeep at the new Trident support facilities in Bangor and King's Bay. At these locations, corrective and periodic maintenance beyond the ability of the crew was conducted. These custom maintenance facilities, along with the extra volume and equipment access in the submarine design, helped maximize the ratio of time the *Ohio*-class boats were at sea versus in port.

During the concept design period, there also was pressure to complete the submarine concept because of SALT. The SALT negotiations began in October 1969. Paul Nitze, the Secretary of Defense's representative at the negotiations, reported that the Soviet delegates were especially interested in the American SSBN replacement. He stressed to Secretary of Defense Melvin Laird that a decision on the proposed FBM platform would give the Americans leverage at the talks.[15]

The final configuration of the submarine was submitted to Congress in January 1972. It included an accelerated ULMS schedule and a missile tube that was ten feet taller and nine inches wider than the

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[14] TRIPER thus reduced the mean time to repair equipment failures on submarines returning from patrol.

[15] Schumacher, 1988a.

tube originally conceived in the Super 640 plan.[16] The new submarine would have a 42-foot hull diameter, displace 18,700 tons, and be powered by a new-design, natural-circulation reactor plant. It would be the largest submarine built in the United States to date.

Acquisition Strategy

EB was awarded a cost-plus-fixed-fee subcontract to design and build a land-based prototype of the propulsion plant in upstate New York in advance of ship construction.[17] A separate cost-plus-fixed-fee Navy contract was subsequently awarded to EB in 1972 to design the rest of the submarine.[18] Both contracts required constructing a full-sized wood mockup of the propulsion plant to aid and validate the design process before any steel was cut.

Many believed that fixed-priced contracts offered the only reliable means of discouraging unnecessary schedule delays and cost growth. This view led Congress to expect a competitively awarded, fixed-price contract for the delivery of the USS *Ohio,* the lead ship in the class, in 1977.

Proposals from Newport News and EB were received in November 1973 for the USS *Ohio* construction contract. The Navy believed that the award would be made on the basis of the lowest total evaluated target price. The shipbuilder's proposals were to take account of the following conditions[19] specified in the Request for Proposal:

- The contract was to be a fixed-price incentive type with an incentive ratio of 75/25 (75 percent of costs above, or savings below,

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[16] This tube was about 60 percent larger than the tube for the Poseidon missile and would not fit into an existing or modified Polaris submarine.

[17] The subcontract award was made by Knolls Atomic Power Laboratory, an Atomic Energy Commission (AEC) facility then operated by General Electric for the joint Navy/AEC Naval Nuclear Propulsion Program.

[18] General Dynamics Electric Boat, no date.

[19] Schumacher, 1988a.

the target cost would be the Navy's share; and 25 percent, the shipbuilder's share).

- The ceiling price, the amount beyond which the Navy would pay nothing further, would be 120 percent of the target costs.
- The *Ohio* was to be delivered by December 1977.

Neither of the shipbuilder's proposals met any of these conditions. Instead, they proposed the provisions shown in Table 3.2.

The proposals were not acceptable to the Navy; neither one included the Navy's desired delivery date and neither proposed a fixed-price type contract. It appeared to the Navy that Newport News was only interested in the work if it entailed virtually no financial risk to the company. EB proposed greater willingness to share some financial risk with the Navy; more important, it included an earlier delivery date.[20]

After extensive negotiations, the contract for construction of the lead ship was awarded to EB on July 25, 1974. EB agreed to a contract delivery date of April 1979 and further agreed to use its best efforts to achieve delivery in December 1977.[21] The contract, although

Table 3.2
***Ohio* Bid Options**

	Electric Boat	Newport News
Contract Type	Cost-plus-incentive-fee (95/5 share line)	Cost-plus-fixed-fee (no share line)
Delivery	April 1979	May 1981
Target Price	$306,138,078 (unescalated)	$415,834,692 –$116,000,000 (estimated escalation) $299,834,692 (unescalated)

SOURCE: Schumacher, 1988a.

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[20] Schumacher, 1988a.

[21] This contract delivery time line (five years) essentially matched that of the *Los Angeles*–class lead ship, a much smaller, simpler ship.

a fixed-price, incentive type, contained several significant risk-sharing provisions:[22]

- a new, revolutionary escalation clause to protect EB against the adverse affects of inflation. Unlike prior escalation provisions, which protected a shipbuilder only to the extent that contract performance was on time and budget, the new provision protected the shipbuilder even if delivery slipped and costs went over budget, as long as they did not exceed ceiling price.
- a then unheard-of ceiling price set at 152 percent of the target cost
- a "kinked" share line, with decreasing Navy shares in overruns as cost exceeded target costs.

The *Ohio*-class design products were generated on the design side of EB under the separate cost-plus-fixed-fee design contract and then passed to the construction side of EB as government-furnished information (GFI). The design contract was awarded in 1972, two years ahead of the construction contract when competition was still contemplated for construction. To ensure fairness in competition, design products had to be provided as GFI to both competitors. The government's assumption of liability for the design products provided the shipbuilder another important risk-sharing provision in the relationship between the Navy and the shipbuilder. During the *Ohio*-class construction, design changes—whether initiated by the construction yard or by the Navy—inevitably became the subject of cost and schedule negotiations between the builder and the Navy.

EB, the prime contractor for submarine construction, received payments by achieving construction progress percentages. Construction progress was determined by computing separate percentages of completion for labor and for material, then combining them in a weighted completion percentage. Material progress was measured by dividing the incurred cost for material by the estimated total end cost for material. Labor progress was calculated by using historical "S"

[22] Schumacher, 1988b.

curves that plotted percentage completion over time for service crafts and physical progress estimates for "hands-on" craft labor.

EB subsequently implemented a cost and schedule control system (predecessor to today's earned value measurement systems) called the Submarine Computer Oriented Management (SUBCOM) system, for management control, which was validated by the Navy in March 1980. A GAO review in 1986 found that, beginning in the mid-1980s and continuing for two years, the EB cost and schedule control system did not comply with Department of Defense (DoD) criteria or its own SUBCOM system. Some of the problems cited were EB's practices of making retroactive changes to budgets and schedules and of overvaluing the budget allocation for work performed early in the construction cycle. This overstatement of the labor hour budget resulted in less progress than what was reported.[23]

Another important risk-sharing provision contained in the *Ohio* contract involved the supply of government-furnished equipment (GFE). The government bore the development risk of a new design propulsion plant by providing all the reactor plant and most of the major engine room components. Any changes due to prototype testing were the financial responsibility of the government. Communications and strategic weapons system components were also GFE. Although *Ohio* was a completely new design built under a fixed-price contract, the design itself and most developmental components were GFE, greatly reducing the shipbuilder's risk.

Over the next two decades, additional contracts were awarded to EB for the construction of new submarines in the class. The USS *Louisiana* (SSBN 743), the 18th *Ohio*-class submarine, was delivered to the Navy in August 1997.

Designing and Building the *Ohio*-Class Submarines

There were three contractors for the major systems:

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[23] GAO, June 1986b.

- Lockheed Missile and Space Company of Sunnyvale, California, designed and built the missile system.
- General Electric, through its operation of the Knolls Atomic Power Laboratory and Machinery Apparatus Operation in Schenectady, New York, had the contracts for the nuclear propulsion plant.
- EB had the contracts to design and build the submarine.[24]

Because EB was designer, builder, and overall construction integrator, the *Ohio* class avoided some of the problems that had occurred between Newport News and EB during the building of the *Los Angeles*–class submarines, when Newport News was the design agent and both shipyards built ships in the class. The *Los Angeles*–class two-yard arrangement caused additional construction churn due to the time lag in design and construction data delivery and reconciliation from the Navy through the design agent (Newport News) to EB.

Contrary to EB's experience with the previous SSBN class, a far greater number of drawings for the *Ohio* class were considered nondeviation drawings[25] that required EB to obtain authorization from the design yard or the design authority (Navy) before it could change them. On the prior submarine class, about 10 percent of the drawings were labeled ND. On the new-generation *Ohio* class, about 45 percent were ND drawings.[26]

The three main organizations involved in construction oversight paid particularly close attention to the different drawing designations during construction. These were the Navy (Navy Program Manager through the Navy's local Supervisor of Shipbuilding [SUPSHIP]); the shipyard that was concerned with construction quality, cost, and schedule; and the ship's crew, representing the operational commander or ultimate Navy. The ship's crew played a key role in the final shipboard system installation verification, acceptance, and ship systems testing.

[24] Office of the Assistant Secretary of Defense (PA), December 1991.

[25] Nondeviation drawings require the builder to build exactly what the plan specifies, usually for technical or safety considerations.

[26] U.S. House of Representatives, 1981.

The *Los Angeles*–class and *Ohio*-class contracts had different compliance standards in the shipyard to account both for the large parallel workload of overhauls and for the fact that the *Los Angeles*–class construction was largely not ND, while relatively more of the *Ohio*-class construction work was. The overhauls and *Los Angeles*–class work allowed some latitude from the viewpoint of ensuring that shipyard work was completed in accordance with quality assurance details. These different standards on occasion confused shipyard quality assurance practices.

As construction on the lead *Ohio*-class submarine, USS *Ohio*, began in the United States, the Soviets accelerated the design and construction of their next-generation SSBN, the *Typhoon* class, which was delivered throughout the 1980s in parallel with the *Ohio* class. This strategic counterpressure on the United States had the fortuitous effect of alleviating the *Ohio*-class program manager's funding concerns, allowing him to concentrate on technical program issues.

New Facilities

As construction on the *Ohio* class began, EB also faced the heel-to-toe overhaul, refueling, and conversion of Polaris SSBNs to Poseidon missiles and the beginning of heel-to-toe construction of the *Los Angeles*–class submarines.[27] Along with these efforts, EB simultaneously supported emerging repair requirements for the fleet. At the beginning of the 1970s, EB had neither the workforce nor the industrial capability to build the *Ohio* and *Los Angeles* classes in parallel—especially the physical capacity to handle the very large sections of the *Ohio*-class submarines, which were far bigger than for any previous submarine. Recognizing this, the shipyard management took three major initiatives.

First, the *Ohio* class was the first U.S. submarine designed to be built with modular construction instead of being built piece-part. In modular construction, interior systems are built as modules in off-hull facilities and then slid into place in the appropriate hull cylinders. Modular construction requires greater accuracy control, but it saves

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[27] In navy and shipbuilding circles, *heel-to-toe* refers to construction and overhaul being performed on a succession of ships one after another.

time and cost by reducing the amount of work performed after the hull is assembled. In addition, most of the construction and testing is done in parallel for different sections of the submarine, and the hull sections are welded together later in the construction process.[28]

Second, EB developed and expanded a satellite facility at nearby Quonset Point, Rhode Island, a former Naval Air Station that the Navy and the state of Rhode Island provided to EB along with access to surplus government industrial equipment. A workload guarantee reduced the business risk of financing the workforce and facility expansion. Subsequently, EB designed and built a new submarine frame and cylinder-manufacturing facility at Quonset Point.

Finally, a new land-level construction facility was built at the EB shipyard in Groton. There, the new SSBN hull sections would be offloaded and rolled into a covered building to allow joining and construction to proceed year-round regardless of weather conditions. A drydock with a unique level-launch pontoon was also constructed, eliminating building and launching on inclined ways, the typical practice since the early days of shipbuilding.

Logistics innovations on the *Ohio* class, such as the design of maintenance onload and offload paths into the submarine, provided an opportunity for production innovations. To avoid assembling, configuring and testing the complex electronic *Ohio*-class combat system in the shipyard industrial environment, the Navy created a dedicated combat system design, maintenance, and test facility in nearby New-

[28] The latest technology methods, including automated hull section welding and end-loading, would be used to manufacture and outfit hull sections for the *Ohio*-class submarines before barging the outfitted sections to the EB shipyard in Groton for joining, final outfitting, system testing, ship launch, sea trials, and delivery. In addition to man-hour savings, this allowed modular construction, efficient outfitting sequencing, and hull section joining to tolerance levels not achieved before. The thick hull steel and heavy foundations necessary for component sound isolation made submarine construction an ideal manufacturing process to consider for modular construction. Based on this construction technique, the objective now was to accomplish as much work as possible in the shop rather than in the shipyard. In effect, the notional hour equivalent for task accomplishment was one hour to accomplish a task in the shop environment versus three hours in the waterfront building environment versus eight hours to accomplish in the water. This was generally referred to as the "1:3:8 rule." This construction technique, coupled with serial *Ohio* production, allowed EB to quickly achieve an 86 percent production-hour learning curve for the *Ohio* class.

port, Rhode Island.[29] There, each ship system was installed and tested in a nonship construction environment (free of hot work and shipyard debris).

When the shipyard production schedule demanded, the precertified combat system was disassembled and carefully shipped to the nearby shipyard in Groton for installation into the ship via the rapid installation program. Connectivity checks were performed to ensure continuity of testing.

Workforce Issues

While these major investments addressed the efficiency of constructing the *Ohio* class and the industrial capability needed to build the vessels, they did not come to grips with the pressure on the workforce. To do this, EB began a major workforce expansion in 1972.[30] A rapid expansion of EB's workforce from about 11,000 to 29,000 was intended to address not only the impending *Ohio*-class workload but also the backlog and delays in *Los Angeles*–class construction.

The large shipyard work backlog and increasing union roles emboldened the local union, and in 1975, one year after the *Ohio*-class construction contract was received, the Metal Trades Council launched a 21-week walkout. This delayed the construction completion of the first *Ohio*-class submarine by two months.

Another Metal Trades Council strike occurred in 1988, when 10,000 workers walked out of the EB shipyard during construction of the *Los Angeles*, *Seawolf*, and *Ohio*-class submarines. This strike took place after the union rejected EB's proposal of annual lump-sum payments instead of annual wage increases that would compound over time. EB officials stated that lump-sum payments were necessary because they were unable to predict future workload and EB needed to remain competitive with Newport News, which at the time paid its workers less than EB.

During the 1988 strike, it was difficult to find additional local employees because of the labor shortage in Connecticut. Nonethe-

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[29] This facility was called the Trident Command and Control System Management Activity.

[30] U.S. House of Representatives, 1981.

less, seven weeks into the strike EB reported that the walkout had not yet put most of its submarines behind schedule.[31] The strike finally ended on day 100, after EB and union negotiators reached a contract agreement.[32]

EB's initial acceptance of an aggressive delivery schedule for the *Ohio* class put additional pressure on workforce development. In addition to a new construction workload consisting of six *Los Angeles*–class submarines, EB also contended with a 2 percent to 2.5 percent worker attrition rate per month.[33] Thus, shipyard management had to train and supervise an inexperienced workforce as well as overcome the lagging schedule of the competitively procured *Los Angeles*–class submarines and the schedule pressure and quality assurance concerns on its sole-source *Ohio*-class program.

Quality Control Issues

In 1979, the year the USS *Ohio* was launched, the program encountered its first major quality assurance issue. EB discovered nonconforming steel—that is, steel not fully meeting design specifications—during an internal audit of its warehouse stock. None of the steel was, or could be, used in submarine safety (SUBSAFE) or pressure hull applications; nonetheless, it had to be quickly isolated throughout the stock system and reviewed prior to issue.

The steel, intended for secondary applications such as small foundations, hangars, and shims, had been purchased between 1970 and 1979. All purchase orders were reviewed, and about 12 percent were found to be for nonconforming steel. A full review was conducted of the 126,000 locations where the steel was used throughout the ship. The incident and review caused some construction perturbation. However, the impact on the *Ohio* class was minimal, with only 41 pieces of steel, amounting to 50 pounds, requiring replacement.

In November of the same year, the Navy SUPSHIP and EB together discovered incomplete non–pressure hull welds and, in some

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[31] Ravo, 1988.

[32] "Walkout at Electric Boat Ends on Its 100th Day," 1988.

[33] U.S. House of Representatives, 1981.

instances, missing weld inspection records on a *Los Angeles*–class submarine. This effectively brought shipboard welding to a stop while a comprehensive welding program audit was conducted to determine the nature and extent of the problem. The shipyard investigation traced the problem as far back as 1975.[34] Further, it correlated the weld problem with the rapid buildup of the workforce. A complete audit of *Ohio* class and all other shipboard new construction welds was required. Of the 117,400 welds inspected on the *Ohio* class, 2,502—about 2 percent—were found to be faulty and had to be repaired or replaced. Alternatively, of 4,132,000 inches of weld inspected, 18,700 inches, or 0.5 percent, were repaired or replaced.

The shipyard then instituted a welder retraining program and further tightened oversight of SUBSAFE welds. Once authorized by the Navy in the following year, *Ohio*-class construction resumed.

In 1980, EB upgraded its quality assurance program by establishing new procedures and trend analysis reports to identify, document, and report deficiencies or problems, such as nonconforming steel, incomplete welding, and defective paint. Subsequently, the GAO found that EB was inefficiently implementing its new program and that SUPSHIP had not fully implemented its schedule for evaluating EB's procedures.[35]

Government-Furnished Equipment

In parallel with the welding issue faced by the shipyard, the Navy notified the shipyard of its concerns with *Ohio*-class equipment. The shipbuilder was responsible for building the submarines. However, the ship's systems were populated with large amounts of equipment. This equipment was of two types. Some major system equipment was subcontracted and procured directly by the shipyard that was then responsible for vendor oversight and ultimately proper equipment operation. Such equipment was referred to as contractor-furnished equipment (CFE). The second type of equipment was GFE, which the Navy (gov-

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[34] As early as 1972–1973, welding irregularities had been noted in missile hatch welding during Poseidon conversions.

[35] GAO, 1982.

ernment) contracted and procured directly. This was typically the case for the propulsion plant and some major combat systems equipment. The government was expected to deliver properly operational GFE according to specification and shipbuilder schedule.

At times, the GFE required minor repair and modification. Rather than request the equipment manufacturer to send technicians to make these minor adjustments, the Navy established a process in which EB workers would make the repair or adjustment for a fixed fee. All such changes carried the same fee. The EB cost of some changes was less than the fee; the cost of others exceeded the fee. The plusses and minuses in this process tended to balance out while construction schedules stayed on course.

During propulsion plant testing in 1979, the Navy requested that the shipyard rebalance the large GFE turbine generators that were already installed in the ship, finding them to be out of balance. While this procedure was time-consuming and limited in scope, it was a predecessor to the subsequent request to remove and replace the main turbine rotors after the engine room had been completed, inspected, and otherwise tested. Unlike the rebalancing, which was conducted during propulsion plant testing, replacing the rotors involved major engine room disturbance because it entailed removal and reinstallation of interfering systems and equipment in a completed and tested engine room. Many piping systems and their associated joints had to be removed, reinstalled, and retested. Many electrical systems were similarly affected.

In addition to these two large GFE problems, notifications of defects in GFE were being sent to the Navy by the shipyard at the rate of about 300 per month, at the same time as the shipyard was attempting to complete and deliver the first ship in the class. In 1979 and 1980, more than 8,000 of these notifications were forwarded by the builder to the Navy.[36]

[36] U.S. House of Representatives, 1981.

Design Changes

Although the basic system performance parameters for the *Ohio* class were settled by 1971, weekly design and cost reviews by both the Navy and the shipbuilder continued throughout the decade. As the result of one such design review that took place after the turbine generator rebalancing and turbine rotor replacement discussed above, the shipyard was directed by the Navy to modify the turbine throttle stand foundation. This direction reflected revised design stress calculations. Following this change, a number of significant design changes were directed. Because of associated system impacts, these changes began cumulatively to delay the ship's master construction schedule delivery date.[37]

In August 1982, the Secretary of the Navy decided to introduce the Trident II D5 missile into the SSBN fleet. Beginning with the ninth *Ohio*-class submarine, the ships were configured for the new Trident II D5 missiles during new construction. The initial eight ships were subsequently reconfigured to hold the D5 missiles. The USS *Tennessee* (SSBN 734), the initial Trident II submarine, had her delivery postponed by a year to accommodate the reconfiguration.[38] The Navy modified the contract with EB to incorporate the D5 missile into the remaining submarines to be built. The construction schedules of the tenth and eleventh submarines were also affected, but to a lesser extent.[39] The schedules for the remaining submarines were less affected.

During this time and the follow-on *Ohio*-class construction period, the Navy and EB concentrated on fine-tuning the modular construction techniques begun with the USS *Ohio*. This included upgrading the large hull cylinder handling equipment and improving the automated frame and cylinder manufacturing processes. Halfway through the *Ohio*-class construction, the sectional *Ohio*-class construction plan, including all aspects of module construction—from cylin-

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[37] The delay due to design changes totaled two months.

[38] At the time USS *Tennessee* was delivered, EB had as many as six *Ohio*-class submarines in serial production.

[39] A worker strike at EB during the delivery of the *Tennessee* contributed to some of the delays.

der manufacturing, module prefabrication, and preassembly through outfitting and end-loading—had been steadily improved along a solid learning curve.

In the late 1980s, construction of the *Seawolf*-class submarine was beginning at EB. The termination of the *Seawolf* program was expected to negatively affect the *Ohio*-class construction program.[40] However, contrary to expectation, EB accelerated the delivery dates for SSBN 739 and SSBN 740 by about two months as a result.[41] The last *Ohio*-class submarine, the USS *Louisiana*, SSBN 743, was delivered to the Navy in August 1997.

Areas of Schedule Delays and Cost Growth

Schedule Delays

Overall, the initial *Ohio*-class submarine design and construction schedule was optimistic and perhaps even unachievable and led to a series of delays. Those delays were due to a combination of quality assurance issues, design changes provided by the Navy late in construction, labor disputes with the local trade unions, and inefficacious workload distribution among shipbuilding contracts within the shipyard.[42]

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40 Office of the Assistant Secretary of Defense (PA), 1991.

41 Office of the Assistant Secretary of Defense (PA), 1991.

42 The initial target completion date for construction of the first ship was December 1977. The metal trades strike began on July 1, 1975, and was settled on November 26, 1975. As a result of the strike, construction was delayed and delivery slipped to April 1979, the original contract delivery date. During 1977, the shipyard issued a revised *Ohio*-class master construction schedule that delayed USS *Ohio* delivery until April 1980, then revised that schedule to reflect a delivery date of October 1979. At this point, the Navy reassessed the shipyard's schedule and found it possibly achievable but optimistic. In 1978, the USS *Ohio* delivery was again delayed to November 1980. This schedule change was made by EB as it sought to address the impending impact of several *Los Angeles*–class submarines and the USS *Ohio*, all converging on 1981 delivery dates. On August 28, 1980, EB informed the Navy that the lead *Ohio*-class ship's delivery date was rescheduled from February 1981 to June 29, 1981. In this letter, the shipyard did not communicate any schedule delay for the follow-on submarines, but another letter dated October 3, 1980, was written to the Navy saying the current schedule for ship deliveries was no longer realistic. See Office of the Assistant Secretary of Defense (PA), December 1980. The USS *Ohio* delivery date was then pushed to

In total, there were six revisions to the delivery date for the first-of-class *Ohio* vessel. Table 3.3 shows the original delivery date and the subsequent revisions to the delivery schedule for the first boat.

The lead Ohio-class submarine, the USS *Ohio*, was delivered on October 28, 1981, to the Navy, and its commissioning ceremony was held at EB in Groton on November 11, 1981. Based on EB's initial fear that the post-shakedown availability (PSA) of the first *Ohio*-class submarine would affect the delivery of the two follow-on ships, a contract modification to extend their delivery dates by 28 days at a maximum cost of $2 million was put in place. However, the PSA was unremarkable, and another contract modification followed for the subsequent two ships, which called for no delay and no cost increase.[43]

Table 3.4 shows the evolving delivery dates for the first eight *Ohio*-class submarines (the Trident I boats).

Table 3.3
***Ohio*-Class First-of-Class Delivery Date, Original and Revised**

		Delivery Date
Original		April 1979 (Target: December 1977)
Revised	1	April 1980
	2	October 1979
	3	November 1980
	4	February 1981
	5	June 1981
	6	October 1981

October 1981. By this time, there had been six changes to the delivery date that delayed the vessel by a total of 46 months. EB had scheduled a total of six *Los Angeles*–class submarines and the USS *Ohio* for delivery in 1981. To meet this goal, the shipyard reorganized its labor force on those submarines at the expense of remaining submarines under construction; as a result, progress was delayed on the remaining submarines under construction and their delivery dates were rescheduled. See GAO, 1982.

[43] GAO, 1983.

Table 3.4
Electric Boat Division Delivery Schedules for the First Eight *Ohio*-Class Submarines, by Hull Number

Ship	Original Contract	December 1980 Estimate	April 1981 Estimate	April 1982 Contract	Delivery to Navy
726	April 1979	June 1981	October 1981	October 1981	October 1981
727	April 1980	November 1981	October 1982	September 1982	August 1982
728	December 1980	July 1982	August 1983	June 1983	June 1983
729	August 1981	March 1983	April 1984	February 1984	January 1984
730	April 1982	November 1983	December 1984	October 1984	September 1984
731	December 1982	July 1984	August 1985	June 1985	April 1985
732	August 1983	March 1985	April 1986	February 1986	November 1985
733	May 1986	May 1986	December 1986	October 1986	August 1986

SOURCE: GAO, 1982.

In addition to delays caused by labor actions, construction time frames were delayed because of quality assurance, design, and other problems reported by EB and the Navy. The delays in the *Ohio*-class construction program were the subject of close congressional scrutiny and testimony before the congressional Senate Armed Services Committee (SASC) by both the Navy and EB.

Cost Growth

In mid-1981, EB's cost reports finally reflected the schedule changes experienced to date. Table 3.5 shows the results of the three *Ohio*-class contracts as of that time.[44]

[44] GAO, 1982, p. 10.

Table 3.5
Cost Escalation in the First Three *Ohio* Contracts (millions of FY81 dollars)

Flight	Number of Submarines	Current Target Cost	Contract Baseline[a]	EB Budget	Estimated Cost Growth
I	4	916,075	1,524,362	1,721,862	197,500
II	3	924,025	1,353,585	1,367,517	13,932
III	1	350,837	473,990	473,990	0
Total	8	2,190,937	3,351,937	3,563,369	211,432

[a]Includes target cost, an estimate of authorized, unpriced work, and estimated escalation payments, paid separately from contract price.

At the beginning of the *Ohio* program, EB's labor pricing reflected anticipated efficiency gains from the advanced manufacturing and process techniques instead of actual labor experience; however these manufacturing techniques were to be primarily used at the Quonset Point hull module facility, not the shipyard.

The man-hours to build each of the first eight *Ohio*-class submarines steadily dropped as EB gained experience and streamlined production. The Trident Flight IV contract signed in 1982 for the ninth boat (the first D5 boat) reflected direct labor hours 23 percent higher than EB's 1981 budgets for Trident Flight II ships under construction. Both the Navy and EB considered these hours reasonable for the ninth *Ohio*-class boat; however, government auditors cautioned Congress that EB had formally advised the Navy during negotiations for the ninth boat of forthcoming significant increases in labor hours for ships under construction.

At a level above labor hours, the basic unit of measurement for labor progress in building a submarine was the individual task or work authorization. Each submarine had several thousand work authorizations, about one-third of which would be open at any time during construction. Each authorization had a budgeted number of labor hours to complete the work. The shipyard had guidelines for estimating task completion on regular and large work authorizations exceeding 1,000 labor hours; this was done bi-weekly.

In the early 1980s, the Navy validated an EB management system for cost and schedule control (SUBCOM). Soon thereafter, however, the Navy noted a number of shipyard practices that deviated from the system as originally approved. The problem of greatest concern was EB's practice of making retroactive changes to budgets and schedules and overvaluing the budget.[45] This resulted in greater reported progress. Internal Navy audits noted this possibility as early as 1980. In October 1980, the Navy representative, SUPSHIP, had informed EB that it was aware of many instances of retroactive schedule and budget changes. Within a year, the Navy had directed that the shipyard stop this activity.

In 1982, the Navy informed the shipyard that it would use its own SUPSHIP estimate of progress because EB's estimates were considered unreliable. This in effect suspended progress payments until revisions to the EB system that were acceptable to the Navy were complete in 1983.

Some cost growth for the *Ohio*-class contract initially occurred because the Navy continued to use the EB labor budgets as the basis for original and updated contract costs even though it knew that they were unrealistically low.[46] The contract awarded in February 1982 reflected substantial increases over previous contracts in direct labor hours to build the submarine.

Life-Cycle Issues

Early in the program, the Navy recognized the importance of high operational availability for each boat compared with the option of a larger fleet size. The *Ohio* design allowed additional access space and removal paths to provide for quick removal and installation of equipment. Two new bases were constructed, one on each coast, with drydocks and extensive facilities for the maintenance of both the submarines and the equipment removed during the periods between patrols.

[45] GAO, 1986b.

[46] GAO, 1982.

A robust rotatable pool of spare parts was funded to allow removal and replacement of equipment and the repair of removed equipment while the submarine was on patrol. All these innovations and investments have resulted in the high operational availability achieved by the *Ohio*-class submarines.

Following *Ohio*-class construction, the Navy put in place life-cycle support contracts for the ship's strategic (navigation/fire control, guidance) and propulsion plant systems. The Navy also contracted with EB to be the planning yard for the *Ohio*-class submarine system. As the planning yard, EB was responsible for individualized ship design drawing continuity over the life cycle of the *Ohio* class. The shipyard also was responsible for support services ranging from alteration conceptualization through design resolution, integration, installation, and testing.

Fleet support, including technical problem liaison and advance planning as well as design and engineering support for overhauls or repair availabilities, was contracted to EB as the initial builder. Three separate U.S. Navy Directorates (Strategic Systems Programs Office [SSPO], SEA 08, and SEA 07) manage the *Ohio*-class life-cycle support contracts.

Conversions to SSGN

The *Ohio*-class submarines were originally designed for a 30-year life but were later certified for a 42-year life-cycle composed of 20 years of operation and a two-year midlife refueling overhaul, followed by another 20 years of operation. In 1994, a strategic Nuclear Posture Review (NPR) recommended operating 14 *Ohio*-class submarines rather than a fleet of 18 SSBNs.[47] This recommendation prompted interest in converting the first four *Ohio*-class submarines (SSBNs 726 through 729) into nonstrategic submarines called nuclear cruise missile submarines (SSGNs). In 2001, the administration requested funding

[47] O'Rourke, 2008b.

for two conversions. Congress provided funding for the two additional ship conversions in the following year.

EB was awarded a cost-plus-incentive-fee contract worth $222 million for the conversion of the first *Ohio*-class submarine (SSBN 726) and for long-lead-time material and conversion planning of the SSBNs 727 and 729. The contract also included pricing options for the conversion of SSBN 728.[48]

The conversions and refueling were performed at the Puget Sound Naval Shipyard (SSBNs 726 and 727) and the Norfolk Naval Shipyard (SSBNs 728 and 729). Again, EB, the original designer, was the prime contractor for the program; as such, it was the conversion integrator for all four ships and managed the design and completion of the conversions. SSGN 726 began its first post-conversion operational patrol in late 2007, about 26 years after it was originally delivered. The conversion was accomplished using dual-shipyard design/build techniques recently proven on the *Virginia*-class construction.

The conversions have made the SSGN capable of delivering special operations forces ashore and of carrying and launching up to 154 cruise missiles. The strategic missile system was replaced with tactical missile systems and other ship systems were replaced and modernized as well. SSGNs operate from the same Trident support facilities in Bangor, Washington, and King's Bay, Georgia, from which SSBNs operate. EB, the original design yard, continued as the planning yard for both classes of submarine.

Lessons from the *Ohio* Program

The *Ohio*-class program followed the same strategy as earlier nuclear submarine programs: Minimize the technical risk by adopting the best technologies available at the time while pushing technology boundaries in only a few select areas. Although the *Ohio* was the largest submarine built in the United States at that time, the program proceeded with few technical problems and is largely considered a successful pro-

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[48] Office of the Assistant Secretary of Defense, 2003.

gram. It benefited from a robust industrial base and ample funding during a period of increasing defense spending to counter growing Soviet threats. The important lessons in the program are listed below.

A new SSBN program is a national asset and must be carefully managed as such. Unlike an attack submarine, a ballistic missile submarine is one of the key legs in the U.S. nuclear deterrence triad. The strategic and operational contexts of the platform are not solely the purview of the Navy. The program manager must manage the requirements and concept development processes sensitive to this more demanding mission and the broader stakeholder and Navy requirements base. The program manager must be open and forthcoming with the broader defense community and the Congress on the status and progress of the program. He or she must also be organized and prepared to arbitrate concerns among various stakeholders.

Operational availability is a key parameter of an SSBN and must be designed into the platform from the start. The Trident ILS system was innovative from three noteworthy viewpoints. First, SSPO thought out of the box and "did the math." Early on, the program manager recognized that a support approach involving intermediate, activity-centered maintenance performed at bases located ashore in the continental United States was preferable to a worldwide, multi-tender Polaris/Poseidon support system. While expensive, it would provide clear advantages, including lower transportation costs and better vendor and contractor support for the ships.

Second, from a design viewpoint, SSPO took advantage of the space provided by the *Ohio's* size to design in the revolutionary ship changes that would optimize the new approach.

Mainly however, the *Ohio* program recognized for the first time that when a choice must be made between investments in high-risk developmental technologies to enhance platform stealth versus investments in platform operational availability, operational availability is the key to strategic deterrent viability. This was a key philosophical departure from the initial Polaris system approach, which emphasized force size. SSPO also recognized that this new philosophy of operational availability had to be designed into the entire Trident system from the outset.

The risks involved with incorporating unproven new technologies must be understood and the program structured accordingly. The *Ohio* program used the best technologies available at the time, many of which had been demonstrated and proven on submarines in the fleet. As such, the *Ohio* was a technically low-risk program. This is not to imply that the *Ohio* was a low-technology submarine; it went to sea with the best technology available. The main risk in the program was building a submarine that was larger than any previously built in the United States. Adopting a modular build strategy and expanding facilities to accommodate the larger hull sections helped keep the program from serious cost overruns and schedule delays. Agreements between the Navy and EB on the use and funding of the Quonset Point facilities helped achieve a reduction in production hours for successive boats.

Design changes must be minimized once construction begins. Design changes late in construction, particularly those that disturb major equipment arrangements, are likely to result in cost growth and schedule delays. To the extent possible, the program manager must freeze the design once construction starts. Mockups play an important role in understanding required design changes. Physical mockups were part of the *Ohio* contract. Modern 3D computer-assisted design (CAD) software can preclude the need for physical mockups in some cases.[49]

Flexibility and adaptability are important design considerations, although cost implications must be considered. Important decisions during the *Ohio* design facilitated changes made after the platforms were put into service. The *Ohio* class adapted to the new D5 missile with minimal impact because the designers had the foresight to build the missile tubes larger than required for the C4 missile. The SSBNs were converted to SSGNs although the missile tubes did require significant work in removing the tube linings to accommodate the cruise missile launchers. The program manager must recognize that the original operational requirements that drive the design of the platform are likely to change due to new missions or new threats; thus, flexibility and adaptability of the platform are important considerations. How-

[49] However, in the *Virginia* program, which was largely designed with CAD software, partial physical mockups were still required and proved useful.

ever, the program manager must also weigh the cost of increased margins and flexibility against the potential future costs of not including the flexibility and margins.

The schedule must be realistic, but managers should be prepared to adjust it if problems arise. Considering the industrial environment at the EB shipyard with the *Los Angeles*–class construction, both the Navy and EB were overly optimistic in believing construction of the largest and most technologically sophisticated submarine in the United States could be delivered by 1979 and especially that their "best effort" would result in a 1977 delivery. Faced with the aggressive schedule, the shipbuilder focused on measures to address production efficiency and efficacy. However, a rapid build-up in the workforce also required attention to quality assurance and adherence to construction processes, especially those that address SUBSAFE issues. Large increases in the workforce should be predictable and the program manager and shipbuilder must plan for problems that could occur with an infusion of inexperienced labor. The program manager must assess whether the desired delivery schedule is realistic and should not incentivize schedules that are unrealistic. The program manager should also recognize that problems with the design, construction, or the workforce are likely to occur, and should be prepared to adjust the schedule if warranted.

There must be decisions on whether the Navy or the shipbuilder is best positioned to manage the provision of systems and equipment. The program manager should seriously consider which equipment and systems the Navy should provide as GFE to the shipbuilder. The question of GFE versus CFE basically comes down to who can best manage the cost and schedule risks and the effect on the Navy if equipment is delivered late or outside of specifications. If GFE is late or defective, the program will shoulder the responsibility for any difficulties or corrective actions. When deciding on GFE versus CFE, the program manager must consider the equipment development stage and its complexity as well as the vendor's maturity and capacity for risk management.

Because capabilities vary over time, the Navy might be the preferred provider in some cases; in other instances, the shipbuilder might be the best option for managing and supplying the equipment. Developmental equipment may best be handled as GFE for early ships in the class and transitioned to CFE for later ships when the design is mature and stable. One lesson from the *Ohio* program is that management of supplier quality and reliability must be as aggressive as that of other program aspects, such as schedule and overall costs.

Appropriate metrics must be established to track progress on cost, schedule, and quality. The program manager must routinely reassure himself that he has the correct program metrics in place to assess cost, schedule, and performance quality. The metrics should preferably be anticipatory and help preempt quality problems that adversely affect cost and schedule. Although the program manager has little direct control over the industrial workforce, he must have in place the tools to (1) monitor workforce performance as it affects his goals and (2) understand the workforce dynamics so that he can communicate with the shipbuilder and achieve cost, schedule, and performance goals. Variance in metrics—such as expended versus anticipated labor hours—should indicate trouble and be vigorously addressed. Naturally, the Navy's shipyard representative (SUPSHIP) is likely to have the best insight into actual or anticipated program status; therefore, the program office and program manager must have a broad-based and mutually reinforcing relationship.

Stability is key to a successful program. Stable program funding and the continuity of key personnel at the Navy, the designer, and the construction shipyard are key elements in the ability to establish program efficiency. Because adequate funding is seldom assured, the program manager should consider a management organization that can independently focus on both the program funding and the technical aspects of program management. Included in program stability is the assurance of a solvent and reliable vendor base. At the shipyard, continuity of good, persistent management can help overcome many difficulties in construction. Over the course of the *Ohio* design and construction program, SSPO ensured a stream of trained, experienced management personnel. Management continuity helped ensure that there was a consistent Navy-to-shipyard perspective throughout the program and that program problems, once addressed, were not repeated.

Stable, repetitive production can help ensure cost controls and cost reductions. The *Ohio* program both controlled and reduced construction costs through a stable design and the assurance of repetitive construction work. The program manager, to the best of his ability, should establish the future construction program early so that the shipbuilder and the vendors are assured of future work. This can lead to facility investments and workforce planning that will contribute to learning and lower costs.

A sole-source, single designer and builder can lead to reduced costs. One reason the *Ohio* program experienced cost and schedule success was that a single firm was involved in the design and construction of the submarines. Whenever possible, a program should strive to involve only one organization for design and construction. Also, separate design and lead ship construction contracts can lead to additional costs and disputes between the shipbuilder and the Navy as the provider of GFI drawings. Combining the design and lead ship construction in a single contract can reduce costs, especially if competition for construction is not viable. Even with a single contract, the construction of the lead ship should be priced only when the detailed design is sufficiently complete, so that both the shipbuilder and the Navy have enough knowledge to estimate realistic costs.

Realistic cost estimates are important. A program manager's success is ultimately tied to the ability to meet cost goals. It is therefore important that target costs be based on the best available data and not underestimated in an attempt to secure program approval. With the *Ohio* program, EB overestimated the efficiencies possible at Quonset Point when the actual data suggested that labor hours would be greater than estimated. The Navy's shipyard representative (i.e., SUPSHIP) should have a role in validating cost estimates.

Major systems and equipment should be tested off the submarine before installation and integration. The separate test facility for the combat system allowed the discovery and correction of problems in a more conducive environment compared to testing the system after it was installed in the submarine.

CHAPTER FOUR

Seawolf Case Study

The decade of the 1970s saw the beginnings of a long and large *Los Angeles*–class construction program and the start of the design and construction of the *Ohio*-class program. Both EB and Newport News had full order books and large construction workforces. But advances in Soviet submarine technology led to increased concern over the Soviet Union's capability and thus to the beginning of a new class of attack submarines. This new class, the *Seawolf*, is the focus of this chapter.

Background

The *Seawolf* attack submarine program was initiated to develop a follow-on platform to the *Los Angeles* class and was undertaken in response to both a new maritime strategy and Soviet ASW advances.[1] The *Los Angeles* class had been conceived in the mid-1960s to operate with a carrier battle group to gain an attack position against Soviet submarines that were capable of achieving high submerged speeds. It was designed when the Navy had a mid-ocean strategy and chose to avoid offensive operations in the Barents Sea and the Sea of Okhotsk, where Soviet SSBNs might patrol. By the end of the 1970s, two decades of steady Soviet advances had resulted in the *Los Angeles* class losing some of its ASW advantage.

1 Hattendorf and Swartz, 2008, p. 79.

The 1980s brought additional changes that influenced submarine warfare and created the need for a more advanced submarine. Early in the decade, a new maritime strategy was unveiled that served to underpin a 600-ship Navy and the operational objectives of the fleet. The Navy wanted to counter the Soviet submarine fleet as far forward as possible, in the sea denial and sea control zones.[2] At the outbreak of hostilities, U.S. submarines would now be expected to operate far forward, both in the northwest Pacific and the northeast Atlantic. In addition, U.S. submarines would need to detect Soviet SSBNs in these environments while avoiding counterdetection.

By the beginning of the 1980s, the *Los Angeles* class was in full production; the first flight was completed and the second flight was rapidly being delivered. However, while the *Los Angeles* class had the speed needed to conduct carrier support operations and control the sea lanes, the platform did not have capabilities to meet the enhanced ASW mission profile, including conducting stealthy offensive action against Soviet SSBNs in the Soviet "bastions" (Soviet submarines operating in Soviet waters) or operating under ice. This enhanced Soviet submarine capability paved the way for the development of operational requirements for the *Seawolf* class.

Setting the Requirements

As the Soviets fielded improved submarines in the 1970s, the United States began to consider the design of the successor to the *Los Angeles* class. Early concepts for an attack submarine focused on a number of smaller, less expensive designs that included improving the capability of the *Los Angeles* class.[3] However, in 1981, as the new administration ushered in an era of expanded Cold War defense spending and a new maritime strategy, it soon became clear that the *Los Angeles*–class design margins were not adequate to absorb the upgrades that would be required.

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2 Hattendorf and Swartz, 2008, pp. 74–82.

3 Polmar and Moore, 2004, p. 172.

In the new strategic and budgetary environment, the initial concept for a more affordable and less capable platform was set aside in favor of a more advanced platform that would both challenge the Soviet ASW advantage and meet the needs of the new maritime strategy.

The *Seawolf* program, or SSN 21 program (SSN connotes nuclear attack submarine), was initiated in 1982 with early concept development. A special Navy study group, Group Tango, was established to assess future threats and conduct technology feasibility studies. The *Seawolf*'s primary mission would be to hunt down and track Soviet ballistic missile submarines. The priorities in the development of the *Seawolf*'s operational requirements were increased stealth (acoustic silencing) and an improved combat system. Additional mission areas included anti-surface warfare, strike warfare, surveillance, and mine warfare.

These operational requirements were translated into performance parameters by the Navy.[4] A primary objective was to regain the "acoustic advantage" that had been lost to the latest Soviet submarines. A reduction in radiated noise and a significant improvement in sensors and sonar signal processing, as well as improved weapons capabilities, were deemed essential for the submarine to be able to detect and attack Soviet SSBNs without being counterdetected. The sonar effectiveness would be improved through an integrated submarine advanced combat system (SUBACS or, as subsequently renamed, AN/BSY-2).

An important design requirement was a strengthened sail and bow-mounted, retractable diving planes to provide capability to operate in the Arctic. The *Seawolf* class would also have faster speeds (flank and tactical) and operate at greater depths than the *Los Angeles* class. To achieve higher speeds, the Navy selected a ducted propulsor technology.[5]

To operate at the specified depth without the associated weight penalties, the *Seawolf* class was designed to use HY-130 steel. (Previous

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4 Most of these specific parameters are classified.

5 The use of a polymer ejection system for increased speed was investigated but eventually discarded; *tactical speed* is the speed at which a submarine can detect and hold contact on a specified adversary.

submarine classes had used HY-80 steel.) As the requirements process drew to a close, the Navy leadership directed that the *Seawolf* class be able to accommodate a greater weapons payload than the *Los Angeles* class, in addition to having the capability to launch Tomahawks from its torpedo tubes. To accommodate yet-undeveloped larger weapons, eight torpedo tubes were planned, each 26.5 inches in diameter versus the 21-inch tubes on previous classes.[6] The Navy set the notional torpedo payload at 50 to allow the submarine to remain in a forward combat area without resupply for an extended period of time.

These aggressive operational capabilities for the *Seawolf* required significant advances in several technology areas. Reduced quieting, faster speeds, greater diving depths, and larger payloads contributed not only to a large submarine but also to one that would push current design limits. The *Seawolf* would require a new reactor, propulsion system, and combat system, as well as the use of new steel. In many ways, the *Seawolf* program deviated from one of the basic tenets of previous programs: Limit the number of new technologies for a new class of submarines. But these multiple advances in technology were deemed necessary to meet the increasing capabilities of Soviet submarines.

Acquisition Strategy

The *Seawolf* concept formulation process involved the two rival shipbuilders: EB and Newport News. In December 1983, the Navy and DoD approved contracts to both shipbuilders for preliminary designs. After reviewing their submissions, the Navy decided to lead a joint design team with participation from both shipbuilders. The hope was that the team would combine the best design features of each shipbuilder to achieve a "best of both" preliminary design, which would serve as the basis for a competitive detailed design contract award. [7]

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6 Budget shortfalls led to the new, advanced weapons never being developed. As a result, the Navy has yet to take advantage of the larger-diameter missile tubes.

7 Eccles, 1990, p. 27.

The competition for the detailed design contract was heated. The two shipbuilders each fought for a larger share of the submarine design and construction budget. Each had robust construction programs at the time, due to large annual buys of new *Los Angeles*–class submarines, the start of *Ohio*-class construction at EB, and new carrier construction at Newport News. However, Newport News had not designed a new submarine in nearly 20 years and EB had not designed a new attack submarine in an even longer time.

Motivated by the need to manage the capabilities and capacity of its nuclear propulsion plant design resources at both government laboratories and private-sector shipbuilders, the Navy first selected the Bettis Atomic Power Laboratory and its naval architecture/marine engineering subcontractor, EB, to design the propulsion plant and build a mock-up at the propulsion plant design yard. This decision was made while the conceptual phase of the overall ship design was in its early stages.

A subsequent competition was held for the lead detailed ship design contract. Newport News assembled a top-notch team for its design bid and was well prepared to improve the preliminary design and deal with the Navy's priorities in the emerging design. EB's experienced designers were working on the propulsion plant design contract, but a strike by the marine draftsmen hampered EB's design proposal.

Although the Navy recognized the potential problems associated with a split-design approach, it awarded the lead detailed design contract to Newport News as the lead design yard. Because the propulsion plant was already being designed at the EB shipyard in Groton, Connecticut, EB was awarded a subcontract by Newport News as a participating design yard for the design of the aft end of the submarine and the nonpropulsion aspects of the engineering spaces. Newport News had the detailed design work for the front end of the ship and the integration effort for the complete ship. Newport News was initially awarded $303 million as the lead design yard and EB received $48.8 million under a subcontract as the participating design yard.

The *Seawolf*-class combat system (AN/BSY-2) was contracted under a separate acquisition program with General Electric under a fixed-price-plus-incentive-fee contract and was being designed concurrently with the ship. The combat system was to be provided as GFE to the shipbuilder.

The original plan was to build 29 submarines in the class. With such a large production run, the Navy hoped to reap the benefits of competition for the construction contracts. This desire for future competition led to a requirement that the design data be usable at either shipyard to allow informed bids on the construction of the boats. As a result, the design was not optimized for production in either shipyard.

Detailed platform design began in January 1987 under an interim contract. The eight-year cost-plus-fixed-fee design contract was finalized in April 1987. The Navy expected that the contractors would have enough of the initial design work complete by May 1988 to begin soliciting construction bids; the goal was to have 70 to 80 percent of the detailed design complete before construction began in November 1989.[8] These goals proved overly ambitious—partly due to the split-design approach involving the two shipyards, partly due to the technological risk associated with the desired operational requirements.

The end of the Cold War and the call for a peace dividend led to a reexamination of the need for a large number of new, highly capable, and thus costly, nuclear attack submarines. Ultimately, the high cost of the *Seawolf*-class submarines and the loss of a significant Soviet threat resulted in only three submarines being built of the 29 in the original build plan. This reduction eliminated the opportunity for competitive construction awards, one of the tenets for developing a design that was not optimized for production at a specific shipyard.

Designing and Building the *Seawolf*-Class Submarines

The detailed design approach for the *Seawolf* class allocated major ship systems and the ship's ten design areas between the two shipyards. The two-year period between the design contract award and the award of the lead ship contract was intended to accommodate increased design activity, conflicts, and their resolutions that could result from the

[8] GAO, 1988.

multiple designers, and the development of the new technologies needed to achieve the desired operational performance.[9]

Although a split-design strategy was used in other acquisition programs at the time, it was largely unproven.[10] The motivation for the strategy came from a desire to maintain submarine design capability at the two shipbuilders. While split design did allow both shipyards to maintain submarine design capability, it eventually created numerous problems.

Each shipbuilder had its own design/build approach. EB used both CAD tools and manual drawings to provide the design detail needed for building the submarines. Newport News used a CAD system exclusively, which differed from that used at EB. Each shipyard had a different convention for numbering parts. Moreover, construction details—how cables were run through the submarine, how ventilation was built, what standard pipe hangers and electrical connections to use—were different. These differences required a high degree of cooperation between the two shipbuilders. Unfortunately, the looming competition for construction led to a lack of cooperation as each shipyard was reluctant to share "company secrets."

The Navy had to act as a mediator in this environment. It had to intervene at high decisionmaking levels to resolve issues surrounding detailed design drawings and to approve design data. The unanticipated need for interyard drawing coordination and problem resolution led to design schedule delay and increased cost.

Despite the two-year interlude between the start of detailed design and the award of the lead ship construction contract, the original goal of having 80 percent of drawings complete before construction fell behind schedule. Competitive bids for construction were solicited even though the design was only about 5 percent complete.

The construction contract for the USS *Seawolf* was awarded to EB in early 1989 for a low bid of $726 million. But with the lag in design, the build schedule slowly started to drive the program.

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9 GAO, 1988, p. 27.

10 The V-22 Osprey was built using a split-design/build strategy and also incurred problems throughout the program.

Newport News drawings had to be converted into EB-specific work packages that provided the build instructions and material lists for construction of USS *Seawolf* at the EB shipyard. These difficulties were compounded when design specifications for certain major systems were changed after construction had begun. In some cases, this required EB to rip out and rebuild some ship system sections. By 1992, the Navy had approved more than 800 specification changes to the design, which were estimated to increase design costs by almost $180 million.[11]

One year later, the estimated cost increase of detailed design was $17 million and the lead ship construction cost had risen 3.5 percent.[12] The *Seawolf*-class submarines were built using the modular construction techniques developed for the *Ohio* class. Large hull cylinders were built at EB's Quonset Point facility and barged to Groton for final assembly and test. The original plan was to accomplish a large degree of outfitting at Quonset Point. However, the delay in producing the design drawing details needed for modular construction and the frequent changes to the design resulted in the cylinders leaving Quonset with little outfitting having been accomplished.

The split-design strategy proved to be risky soon after construction started. The contracts were not forward-looking in the sense that they did not incentivize cooperation between the various design contracts and the lead ship construction contract. Because of the difficulties noted above in design-to-design organization objective alignment and design-to-production methodologies, metrics and workable processes had neither been thought out nor put in place. And there was no straightforward design-to-construction conflict resolution process between the lead design yard and the construction yard.[13]

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[11] GAO, 1993.

[12] GAO, 1994.

[13] This comment is the result of numerous retrospective interviews of members from all parties—Navy, designer, and builder. It does not reflect lack of effort or poor intention; it reflects mostly the effects of a ponderous process and geographic separation of the shipyards.

Facility and Workforce Issues

The *Seawolf* program benefited from new facilities at both EB and Newport News. EB had substantially improved its construction facilities at both Quonset Point and the Groton shipyard for the build of the *Ohio*-class submarines. Newport News had recently built a new land-level facility to construct the *Los Angeles*–class submarines. The *Seawolf* program was prepared to profit from those investments.

Both shipyards also had large, experienced submarine construction workforces. Although the construction workforce was not an issue, the Navy and the shipyards were concerned about the preservation of the design base. With a long projected construction period for the *Seawolf*-class boats and no need for a new SSBN design for over 20 years, there was a looming large gap in the need to design a new submarine.

Quality Control Issues

The HY-130 steel technology was not ready for the lead ship of the *Seawolf* class, but HY-100 steel had been successfully tested as inserts on two *Los Angeles*–class hulls (SSNs 755 and 756) and thus was considered a low-risk technology. However, the basis of the Navy specification for the steel welding rod ingot was not well understood. The specification was based on carbon content versus ingot strength, but the welding rod metal ingot was not properly bracketed by the data. While the lower bound on the specification was backed up by extensive data, the upper bound was determined somewhat arbitrarily. The HY-100 prototype section had been welded with a lower-carbon-content weld wire that was within specifications. The USS *Seawolf* was welded with higher-carbon-content weld wire that was also within specification, but this specification proved to be incorrect. As a result of the use of unfit welding rods and of deficiencies in EB welding procedures, in 1991 cracks were discovered in the mating welds of the *Seawolf*-class initial hull sections, which led to costly reviews and the rework of all faulty welds.[14]

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[14] Eventually, a defective hull section was discarded and the steel used to fabricate construction jigs and fixtures.

Because the weld specification had been faulty, the Navy accepted responsibility for the repairs. The weld issue further complicated the program from the viewpoint of cost overruns, schedule delays, and severe criticism from Congress. Based on a prior informal meeting with Senate staffers, the Navy met with the shipyard to negotiate a weld cost settlement that the SASC would be likely to approve. The shipyard agreed to a supplemental change agreement to the contract.

Government- and Contractor-Furnished Equipment

Because of its previous experience with the *Los Angeles*–class combat system, the Navy believed that completing the combat system program within schedule limitations bore a medium level of risk. To mitigate the scheduling risk, the Navy had planned to develop, test, integrate, and deliver the *Seawolf*-class combat systems software in six years. GAO's program status review in 1987 considered the combat system schedule risk to be high because of the large amount of software required (nearly twice as much as the *Los Angeles* class).[15] Also, the optical data bus was not ready to support the *Seawolf*-class system as planned.

There was a general problem developing in the vendor base, both that used by the Navy and by EB. With an initial plan of 29 submarines in the class, numerous vendors were interested in participating in the program. However, as the number of *Seawolf*-class submarines was cut, many vendors could not make the profit needed to justify the business and either went bankrupt or turned to other, usually nonmilitary, business. Both EB and the Navy had problems finding suitable vendors that could qualify to provide the needed parts and equipment. In some cases, EB had to fabricate components at a cost higher than initial estimates. This key factor rippled though the construction process and contributed to cost increases and schedule delays.

Design Changes

In their initial competitive proposal submissions for *Seawolf* construction, both EB and Newport News had been concerned about the numerous design changes they expected to experience on the lead

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[15] Conahan, 1990.

ship. After extensive negotiations, a contract provision was agreed by both shipyards that enabled their best and final offers. If the design change was in a nondeviation drawing or was a feature included in the front or aft-end mock-ups built by Newport News or EB respectively, the builder would be entitled to an adjustment in contract price (and if necessary, in delivery), provided that the change required rip-out, rework, or a change to material on order. Although tens of thousands of design changes and deficiencies were discovered during construction of the lead ship, this provision and the accelerated review processes implemented by SUPSHIP Groton and EB resulted in resolution of these items expeditiously and without the rancor and contentiousness experienced during the *Ohio* and *Los Angeles* lead ship builds.

Areas of Schedule Delays and Cost Growth

Construction on the lead ship began in 1989. Between then and 1993, the construction schedule was revised four times. The key issues affecting the time line were insufficient design maturity at the beginning of construction and unstable design and specification changes during construction. Specifically,

- Design drawings were incomplete before construction began.
- Improper specifications were used and design specifications were changed after construction began; this was particularly the case with the government-furnished combat system.
- Problems were encountered in preparing and completing work packages.
- Faulty welds were discovered, which required hull rework.
- Immature technology was used.

Despite the Navy's optimism and management initiatives, the AN/BSY-2 combat system scheduled for installation on the USS *Seawolf* experienced its own cost increases and schedule delays. These compounded the *Seawolf* construction problems. The Navy originally provided Newport News with general space and weight information for the system, which the shipyard used to begin designing its portion of the *Seawolf* class. As the concurrent AN/BSY-2 program matured during *Seawolf*-class construction, the Navy later provided the shipyard with updated information that resulted in considerable redesign of the submarine and increased design cost. Despite the fact that the delay of the concurrently developed AN/BSY-2 by over one year was almost fully absorbed by the ship delay because of the welding failure, completing the AN/BSY-2 software on time to support ship delivery in 1997 was still a challenge.

As noted, the hull of the *Seawolf* class was built using a new HY-100 steel that would allow greater depths than previous submarines without incurring the weight penalties of lower-yield steel. In mid-1991 when the submarine was already 17 percent complete, EB discovered hairline cracks joining hull sections together.[16] The cause of this welding anomaly was ultimately determined to be faulty welding specifications provided to the shipyard by the Navy for the new hull material. This major construction fault required extensive rebuilding of the first hull of the planned class, with an estimated cost increase of $68.6 million and a one-year delay in delivery.[17]

These factors, the resulting cost increases, and the dissolution of the requirements basis for the ship made any decision to complete the class untenable. As it became evident that the class size would no longer be 29 ships, the vendor base began to show signs of steady erosion.

Originally, the Navy planned to build 15 *Seawolf*-class submarines through FY95 leading to an eventual class of 29 ships. The plan was to award the lead ship contract, USS *Seawolf* in FY89, two ships each in FY91 and FY92, three ships in FY93 and FY94, and four ships in FY95. However, in the early 1990s DoD undertook the Major Warship Review, a broad reevaluation of Navy needs. This review mandated the reduction of the *Seawolf*-class procurement to one ship in FY91, two ships in FY92, and three ships every two years thereafter.

At the same time, the requirements basis for all DoD systems shifted because of the increased emphasis on the need to support Joint

[16] Polmar and Moore, 2004, p. 311.

[17] GAO, 1992.

Warfare and to operate in the littorals. The *Seawolf* class was not considered a platform that was capable of adapting in mid-construction to this new warfare requirements regime. Additionally, the *Seawolf* program's design and construction problems resulted in delays and cost overruns up to the mid-1990s, making it fiscally unattractive. By the time of her commissioning in 1997, the first SSN 21–class ship, USS *Seawolf,* had been delayed by 25 months. Cost growth on the first ship of the class was estimated to be 45 percent above initial cost estimates. Given the changing requirements environment and growing budget constraints, the superior performance parameters of the *Seawolf* class could not justify its cost.

In 1990, the administration proposed truncating the *Seawolf* class to one boat. Congress, however, authorized a continuation of construction on the second boat of the class and authorized $540 million to support the submarine industrial base until the beginning of a follow-on lower cost submarine program by either resuming construction on the third *Seawolf* class or restarting construction on the *Los Angeles* class. DoD in the meantime commissioned a study to investigate whether it would be better to stop submarine construction entirely and reconstitute the industry in the next century or to continue low-level construction to maintain the industrial base. This study found that the costs of building the third *Seawolf*-class submarine versus stopping and reconstituting would be about equal but maintaining a low-level rate of production bore less risk.[18] Congress therefore decided to build the third *Seawolf*-class ship.

Design and construction of the *Seawolf* class spanned 15 years from early concept development in 1982 to commissioning of the first ship of the class in 1997. The original cost estimate in the 1980s had been $38 billion for 29 ships; a 1999 estimate of the three-ship program was $16 billion.[19] The acquisition program ended with the delivery of the final boat, USS *Jimmy Carter,* in 2005.

[18] Birkler et al., 1994.

[19] Polmar and Moore, 2004, p. 313.

Life-Cycle Issues

With most of the focus on achieving the aggressive design requirements and building the submarine, little attention was paid to the life-cycle support of the *Seawolf*. Cost growth resulted in equipment decisions based largely on initial acquisition cost. Expensive materials were used to reduce weight, which resulted in large repair and replacement costs. The total ownership cost of the submarine, from design through disposal, was largely ignored.

A compounding problem for life-cycle support is the small size of the class. There are only three *Seawolf*-class submarines and one, the USS *Jimmy Carter*, is very different from the other two. The small size of the class makes maintaining a support system difficult and costly.

Lessons from the *Seawolf* Program

Many of the lessons from the *Seawolf* program replicate those from the *Ohio* program. However, there are some important lessons from *Seawolf*, especially in how decisions deviated to some degree from those made in previous programs. These lessons deal primarily with technology risk and acquisition strategy:

The program manager must understand technology risk and how to reduce it. Many factors influenced *Seawolf* design. Chief among them was the understanding that the ship should be the most capable ASW platform built by the United States to date. This factor—coupled with the loss of U.S. ASW advantage for the first time and a decision to aggressively regain it—was instrumental in setting the stage for a high-risk program. Unlike previous submarine design efforts, the *Seawolf* program pushed several technology boundaries because of the desire to significantly increase the capabilities of U.S. submarines in response to the growing capabilities of Soviet submarines.

A new submarine design and construction effort predicated on aggressive technology insertion to satisfy operational requirements will likely insert extraordinary and unpredictable risk into the program. However, circumstances may warrant the use of multiple new technologies in a new submarine design; if that is the case, managing the technology risks will be challenging. The program manager should expand the feasibility study process to ensure that technology development risk is clearly understood and that the likelihood of program cost and schedule increases are known. In doing so, he must critically assess the state of technology or technology risk and assess whether industry is stretching or promising beyond its capability or beyond the "art of the possible."

If the program manager knows he has embarked on higher-risk technologies, he should identify "off-ramp points" at which the technology will be abandoned and the program requirements reduced in favor of a lower-risk solution. This should be done before the overall design and construction program is jeopardized.

A well-executed acquisition strategy is central to the success of a new submarine program. About two decades passed between the design of the *Los Angeles* class and the start of the *Seawolf* design. A combination of competent and proven design capabilities and processes underlies submarine acquisition. The *Seawolf* approach, which melded competing design concepts, sought to capitalize on the capabilities of the two U.S. submarine designers. It also hoped for competition for ship construction, so that designs could be built at both shipyards.

However, this approach produced a complex and eventually counterproductive process in which the ship design responsibility was segmented and design management became problematic for both the lead designer and the Navy. Despite attempts to mitigate design process difficulties, the *Seawolf* program highlighted the importance of persistently and meticulously managing and incentivizing the process to support overall program goals.

In hindsight, an acquisition strategy that involved a single design/construction prime contractor may have resulted in lower cost growth and schedule delay. Decisions in this regard must weight several factors, including the potential for future competition, the future health of the industrial base, and the overall strategy for shaping the nuclear submarine industrial base. Of course, costs must also factor into decisions.

As the *Seawolf* design schedule began to slip, another crucial decision presented itself—the extent to which design completion should prejudice construction start. Construction of *Seawolf* began with less than 10 percent of design complete. As noted, this caused significant churn later in the program because of multiple change orders. In retrospect, construction start should have been delayed to await design maturity, a move that likely would have saved costs. Thus, one lesson from *Seawolf* was that construction should not begin until arrangements are 100 percent complete and overall design is substantially (greater then 80 percent) complete.

Good congressional relations are important for program success. Navy acquisition programs are resourced by Congress. Because of its cost and the changing strategic environment, the *Seawolf* program was the object of near continuous congressional scrutiny. In light of this and the nationwide network of suppliers and vendors affected by the program, the program office made the sound decision to preemptively keep the Congress informed of program changes. This "open book" approach reinforced congressional confidence in the program management and lessened the potential program impact of both the steel and combat system difficulties.

However, policymakers do not have endless patience. The erosion or fading of the need for a major acquisition program, coupled with continued cost increase, will likely (and appropriately) lead to its cancellation.

The nuclear submarine vendor base is a critical underlying component of the national industrial capability. When the *Seawolf* class size began to decrease from the initial 29 ships, the vendor base began to waiver. As a result, considerable effort was required to resize the base for a three-ship class. In all cases, the program manager should anticipate the need to carefully manage the vendor base.

Moving to the First Post–Cold War Submarine Program

An important aspect of the *Seawolf* program was the continuing philosophy in the nuclear submarine Navy for growing future program leaders. Many junior officers learned hard lessons from the *Seawolf* program, lessons that would serve them well when the next program started.

The Navy as a whole learned from the turbulence of the *Seawolf* program that old threats fade and new threats emerge. It had became clear that a radical new way of thinking was needed to ensure the survival of the nuclear submarine force. Most important, EB, whose only product line was nuclear submarines, was facing a less-than-promising future.

CHAPTER FIVE

Virginia Case Study

The demise of the *Seawolf* program resulted from a high-cost submarine designed for a threat that no longer existed. The Navy faced a significant gap until a new SSBN design could be developed. It realized the need to start a new attack submarine design effort both to maintain the desired force structure and to sustain the design resources in the industrial base. At the same time, EB was facing a declining workload with few future prospects for new design or construction work. This environment fostered the advent of the next new nuclear submarine program—the *Virginia* class, which is the focus of this chapter.

Background

The *Virginia*-class attack submarine was developed in the early 1990s as the successor to the *Los Angeles* and *Seawolf* classes. These classes had two things in common: Their roots were in the Cold War, and each had experienced unanticipated cost escalation during the construction programs, though for different reasons. By the early 1990s, the *Los Angeles* class was in full production and the troubled *Seawolf* program was soon to end.

At the beginning of the following decade, the Navy argued that although building one high-cost *Seawolf* submarine every other year might be adequate to sustain the submarine industrial base, it would not be sufficient to sustain both the prescribed submarine force level of 45 to 55 nuclear submarines and the nuclear submarine design base. Faced with the immediate need to address the design base and an affordable solution to the future block obsolescence of the *Los Angeles* class, the Navy proposed a more economical near-term force reduction plan that included decommissioning some *Los Angeles*–class submarines in lieu of midlife refueling. At the same time, to sustain the submarine design and nuclear technology base, the Navy proposed a class of low-cost "new attack submarine," or NSSN (sometimes known as the *Centurion).* The first of these submarines was eventually commissioned as the USS *Virginia*. The NSSN strategy was closely scrutinized and eventually supported by the Department of Defense and Congress.

This submarine would be designed to reflect the dramatic shift in world politics and the national military strategy since the design of the last submarine. The Cold War had ended around 1990 and the Goldwater-Nichols act had been enacted by the Congress in 1986, strengthening the role of the theater commanders and leading to a larger role for the Joint Staff in weapon systems procurement. The new operational requirements environment would predominately address an increasing number of smaller regional conflicts in the littorals. As a result of these changes, the Navy assured Congress that the NSSN would be not only less expensive but also more capable of operations in the littorals, while maintaining undersea superiority against a reduced but nonetheless continued Russian submarine threat.

Design and initial construction of the *Virginia* class spanned 16 years—from the original concept development in 1988 to delivery of the first boat in 2004. Congress remained closely involved in both program oversight and acquisition decisions during this period.

The Navy's review of prior submarine acquisition program lessons learned had highlighted the cost of deviating from the initial requirements once they had been set. As a result, the Navy was determined to set the requirements correctly, cost them, and not deviate from them during design and construction. A less-than-successful program could mean an end to new submarine production for some time and a threat to the Navy submarine force.

At the same time as the Navy was realizing the importance of a successful, low-cost new submarine, the industrial base was also feeling the impact of the truncated *Seawolf* program. Although Newport News had carrier work to sustain its workforce, EB built only submarines, and a gap in submarine production could signal the end of the corporation. Recognizing the urgency of the situation, EB started a process of reengineering itself by reducing staff and seeking ways to cut costs.[1]

Setting the Requirements

The new submarine was intended to be smaller and more flexible than the more expensive *Seawolf* class. In congressional hearings, the Navy maintained that the *Centurion* would be affordable enough to allow production of two submarines per year and thus maintain the force size and industrial base through the turn of the next century.[2] To achieve these savings, the Navy said it would borrow heavily from existing technologies in the *Seawolf, Los Angeles,* and *Ohio* programs. Internally, the Navy was determined to not repeat the mistakes of the distressed *Seawolf* program, which it exhaustively reviewed for technical lessons learned.

At the outset of the requirements determination process, the Navy's mission needs statement assigned seven core missions to the new submarine:

- covert strike
- anti-submarine warfare
- anti-ship warfare
- battle group support
- covert intelligence
- covert mine-laying
- special operations.

Work on cost savings began immediately. To meet cost goals, the Navy conceded some performance parameters. The design priority was

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1 Employment at the shipyard had been reduced from over 14,000 workers to approximately 8,000.

2 *Navy Report on the New Attack Submarine* ("Lennon Report"), 1992.

to match the acoustic capability of the *Seawolf* at the expense of other areas, such as speed and size (displacement). Despite some concern over performance adequacy, Congress began to support the new submarine program on the basis of the Navy's determination to reduce program risk and cost.[3]

In a February 1992 memo,[4] the Chief of Naval Operations (CNO) directed the following focus:

- *Retain* Seawolf *quieting.* Stealth is the cornerstone of all missions that submarines will perform in the future. It ensures the necessary tactical advantage.
- *Reduce maximum flank speed.* Reduce to a speed that provides sufficient mobility and target closure and allows the submarine to operate with other naval units providing rapid response to regional crisis.
- *Maintain elementary combat systems requirements*. Basic capabilities are all that are required. Examine the use of various proven computer technologies in an open architecture design.
- *Reduce weapon payload and weapon delivery rate*. Investigate the use of non-reloadable launchers, such as the vertical launch system, and simplified internal weapon handling systems to optimize payload and launch rate in an affordable manner.
- *Reduce maximum depth*. Although deeper operating depths enhance performance, concentrate the design on depths sufficient to meet the current projected threat.
- *Minimize crew complement*.

The tendency to incorporate immature or high-risk technologies had resulted in construction time delays and cost overruns in previous submarine programs. Thus, technological maturity was a key design consideration for the *Centurion* concept studies. These were classified in four categories of maturity as depicted in Table 5.1.

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[3] *Navy Report on the New Attack Submarine*, 1992.

[4] *Navy Report on the New Attack Submarine*, 1992.

Table 5.1
Levels of Technology Maturity

Technology Basis	Maturity	Specific Systems Considered
Los Angeles/Ohio	Proven technology (low risk)	AN/BSY-1 components Photonics masts HY 80 pressure hull steel
Seawolf	In-service technology upon delivery of *Seawolf*	Hull coatings Pumps Weapons launchers Advanced towed array Wide-aperture hull sonar
Post-*Seawolf* Near-term	Successfully demonstrated or near full-scale at start of *Virginia* design	Composite metals Fiber optics
Developmental technology	Requires concurrent development with ship design (high risk)	Structural acoustic initiatives Composite non–pressure hull stern system

SOURCE: *Navy Report on the New Attack Submarine*, 1992.

Technology that was already in use on existing platforms was considered to be low risk; developmental technologies, particularly those that would have to be developed concurrent with ship design and construction, were considered to be high risk. The consideration of developmental technologies required an assessment of "fall back" technologies and the potential costs of redesign.

Requirements creep in the *Virginia* program came from new "bubble pulse" regulations that changed how the ship was designed for shock. Acoustic performance is typically an area of high technology risk; eventually, changes to *Virginia's* acoustic requirements also necessitated some redesign work.

To mitigate the risk from revolutionary technologies, the *Virginia* program operated on the idea of a "fly before buy" prototype. This strategy required that new technologies be tested on land or at sea and preferably be subjected to the entire mission profile before incorporation into the new platform design. The Navy also retreated to its long-held submarine acquisition philosophy that no more than one major new technology be introduced on any class of submarine and that, to the maximum extent feasible, all technologies introduced on *Virginia* would have been prototyped at sea. Thus, the *Virginia* wide-aperture array, non-penetrating masts, reverse osmosis distilling plants, propulsor, and combat systems had all been proven (most on *Los Angeles*–class submarines) before being incorporated into the *Virginia* class.

Following the Defense Acquisition Board Milestone 0 approval to begin concept definition studies, the Under Secretary of Defense directed the Secretary of the Navy to begin the cost and operational effectiveness analysis (COEA) for a new attack submarine. The COEA guidance included the following alternative analyses:[5]

- SSN-21: Assume continued production of *Seawolf* at one per year at one shipyard, starting in FY96 or in FY98.
- SSN-21(V): Assume at minimum two reduced cost variants of SSN-21 with displacements in the range of 10,000 tons.
- SSN-688I: Assume a variant of the SSN-688 (*Los Angeles*) class that incorporates all available technology starting in FY96 or in FY98.
- New nuclear-powered attack submarine (*Centurion*): Examine a range of alternative new designs that (a) are more affordable ($1 billion); (b) cost less than or equal to the cost for SSN 688I; (c) are smaller than 5,000 tons; (d) have reduced or deleted mission capabilities; and (e) have start dates of 1998, 2002, and 2006.
- *Ohio* (variant): Consider variations on the *Ohio*-class design, including conversion of existing units and differences in tube volume with an emphasis on power projection.
- Conventional: Consider a range of conventionally powered submarines (diesel, fuel cell, hybrid, etc.).

The *Seawolf* class could be produced at one hull every two years, effectively sustaining the construction labor force. *Seawolf* had cost $2.35 billion. In comparison, the *Centurion* unit cost was estimated at $1.4 billion and could be produced at a rate of 1.5 to 2 hulls per

[5] Under Secretary of Defense, 1992.

year. However, the *Centurion* required an estimated $3.5 billion for design and development costs and was less capable than the *Seawolf*.[6] Congress pushed for delay of the *Centurion* until more substantive cost savings could be achieved.

Despite congressional concerns, key performance parameters for the *Centurion* were reviewed and validated by the Joint Staff in 1994, and the Defense Acquisition Board Milestone 1 review approved NSSN to enter Phase I in August 1994. The Demonstration and Validation phase would begin on June 30, 1995.

In 1995, the Navy's Operational Test and Evaluation Force (OPTEVFOR) was able to conduct an early operational assessment (EOA) using a digital database. This was the first time that an EOA had been conducted so early in a project's development. OPTEVFOR's goals were to assess whether the design met the requirements, determine the technical risk of developing new technology, and assess the adequacy of program requirements.

OPTEVFOR found that to complete the first task the Navy would actually need to clarify the requirements: "At first glance, the requirements seemed well defined; however, on closer inspection several requirements parameters were open to various interpretations over a range of values, rather than being specifically nailed down. A requirements clarification team was formed and worked for a week to remove all uncertainty from the requirements. This team produced an Operational Requirements Document (ORD) clarification to ensure that the developing agency and operational testers interpreted requirements the same way."[7]

OPTEVFOR's preliminary analysis expressed concern that the design might not meet the Navy's requirements and that it might not be operationally effective against the most capable threat.[8] The Navy did not concur but maintained that the submarine would be capable against the most advanced threat.

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[6] D'Amato, 1993.

[7] Barney and Zerr, 1996.

[8] GAO, 1996.

Acquisition Strategy

The split design and construction strategy used for the *Seawolf* led the Navy to conclude that having one shipbuilder design and build a ship could save time and money. The initial *Virginia*-class acquisition strategy was to design and build the submarine at a single shipyard.

Further, the 1993 Bottom-Up Review (BUR) concluded that two nuclear-capable submarine building yards could be maintained in the following manner: The third or "bridge" *Seawolf*-class submarine (SSN23) would be built at EB in 1995 or 1996, followed by developing and building a new attack submarine as a more cost-effective follow-on to the *Seawolf* class, with construction beginning in FY98 or FY99 at EB. The construction of a follow-on nuclear carrier, CVN76, would begin at Newport News in 1995. Together, these decisions would maintain two nuclear-capable submarine builders and mitigate any risk to the industrial base.[9]

As a result, in 1996 EB was awarded the lead design contract for *Centurion* under a cost-plus-fixed-fee line item for design of the steam and electric plant, and a cost-plus-award-fee contract line item for the rest of the ship. To ensure that the award fee would not encourage EB to pay more attention to that effort than to the steam and electric plant, a provision was added that prevented EB from receiving any award fee unless the Navy was satisfied with the steam and electric plant effort.

Congress saw the consolidation of submarine building at only one yard as risking some degree of national security through a reduction in flexibility and surge capacity. It was also concerned that sourcing submarine design and construction through only one shipyard would reduce the possibility of competitive bids for future contracts. These political concerns regarding national security, maintaining the industrial base, and fostering competition led Congress to include in the FY96 National Defense Authorization Act a directive that the contracts for the first four ships be alternated between EB and Newport

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[9] Aspin, 1993, pp. 52–57.

News.[10] After delivery of the fourth boat, both shipyards would be required to compete for the construction of follow-on ships.

In December 1996, EB and Newport News proposed to build the first four ships as a team rather than as competitors. This arrangement was consistent with the desire of Congress to develop and maintain submarine construction capability across two yards in a low-rate production environment. Subsequently, Congress allowed this cooperation. EB and Newport News entered into a Memorandum of Agreement whereby they agreed to the following:

- EB would be the single design agent for the contract.
- EB would be the construction prime contractor.
- Newport News would be a major subcontractor with about 50 percent of the work over the construction of every two ships.
- Profit would be split 50/50, regardless of work allocations.
- Each would fabricate the same modules (except the reactor plant) for every ship.
- They would alternate reactor plant module fabrication and whole-ship assembly, test, and delivery.

The design contract was modified in 1998 to add contract line items to build the first four ships.[11] Construction of the first four ships was on a cost-plus-incentive-fee contract. Because of the uncertainty in the submarine vendor base, contractor-furnished equipment was bought under a cost-plus-fixed-fee line item. An additional construction incentive was included to award extra fee if the man-hour learning curve for the first four ships supported the man-hour target for the fifth ship. The incentive payment was timed to coincide with the preparation of the next proposal for the block of ships starting with ship five.

In the initial contract, the prime contractor was responsible for four of the 15 combat systems subsystems: exterior communications, interior communications, nontactical data processing, and ship moni-

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[10] Douglass and Pilling, 1997.

[11] Both Navy and industry interviewees highlighted the importance of making the design yard the lead yard for both design and construction.

toring. The U.S. government provided the remaining subsystems: radar, navigation (including navigation data distribution and display), imaging, and electronics support measures. The government also used a contractor for three subsystems—sonar, combat control, and architecture—and the system-level integration of all subsystems.

Designing and Building the *Virginia*-Class Submarines

U.S. submarine design and construction had improved significantly by the late 1980s. The design and production of the *Ohio* class marked a new emphasis on producibility, that is, the design supported a modular construction process that emphasized cost-effective submarine construction. Nonetheless, both the Navy and industry recognized that, although both *Ohio* and *Seawolf* reflected greater emphasis on producibility, a formal mechanism was lacking for assessing and incorporating promising contemporary commercial productivity.[12]

The *Seawolf* program experienced cost increases and other difficulties because of a high degree of concurrent development and ship construction. Also, in some cases, drawings were issued before designs were fully mature. This sometimes resulted in the need for design revision; in other cases, it required construction rework. The *Virginia* program had to learn from these lessons. As the design and construction of a new submarine drew closer, the Navy realized that the aggressive cost savings could not be achieved if factors that had contributed to cost growth in the *Seawolf* and *Los Angeles* programs were not addressed.

As a result, the Navy conducted an exhaustive post-mortem of the *Seawolf* program and concluded that it could avoid some design and construction cost increases and schedule delays by implementing major management lessons from prior submarine programs that had been emphasized by outside auditors. These included

- contracting with a single shipyard to both design and build the lead ship

[12] Eccles, 1990.

- delaying lead-ship construction until the design was substantially mature
- strengthening the specification development and approval process
- identifying critical components and supply vendors early in the program
- reducing the submarine combat system development risk.[13]

In addition, the *Virginia* program office compiled a database of more than 1,000 discrete technical lessons learned from prior Navy programs to incorporate into the *Virginia* design. These lessons were projected to save the program millions of dollars.

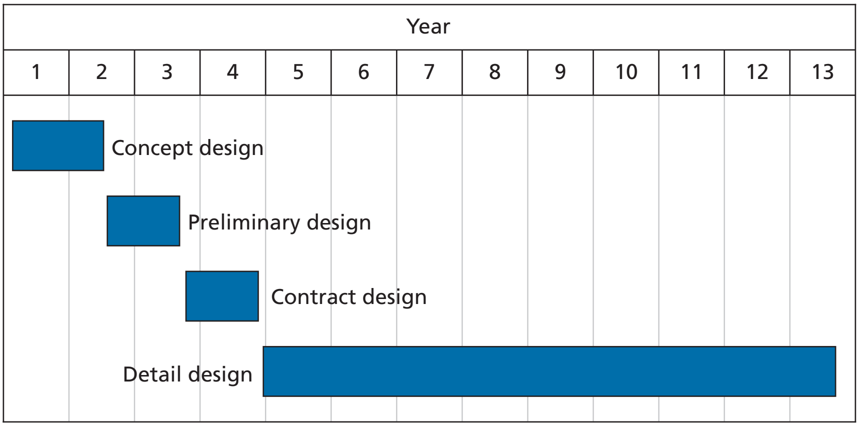
At the same time as the Navy was concerned about the *Virginia's* operational requirement and the submarine design base, EB was concerned about survival. By the end of the 1980s, shipbuilding at EB had begun to shrink dramatically and the workforce was decreasing accordingly. With the cancellation of the *Seawolf* class, future projections for EB's survival without dramatic process change were clouded.

In 1989, EB had initiated an evaluation of parallel industry "best practices" and the options available to address the full spectrum of issues contributing to submarine construction costs and achieving cost-effective change. The study included a review of design management tools, including computer software and the concurrent engineering process. EB's decision was to implement an Integrated Product and Process Development (IPPD) process that allowed it to restructure at the new low production rates while re-positioning itself for growth.

The IPPD process was a distinct departure from the process used on earlier submarine designs. Traditionally, the design process proceeded through a series of lock-step designs—concept, preliminary, contract, and detail—each adding greater detail and ending in a set of drawings for construction of the submarine (see Figure 5.1). Construction started sometime during the detail design phase. Typically, there would be a period between each phase when decisions were made before proceeding to the next phase. These intermediate inter-

[13] GAO, 1994.

Figure 5.1
Traditional Submarine Design Phases



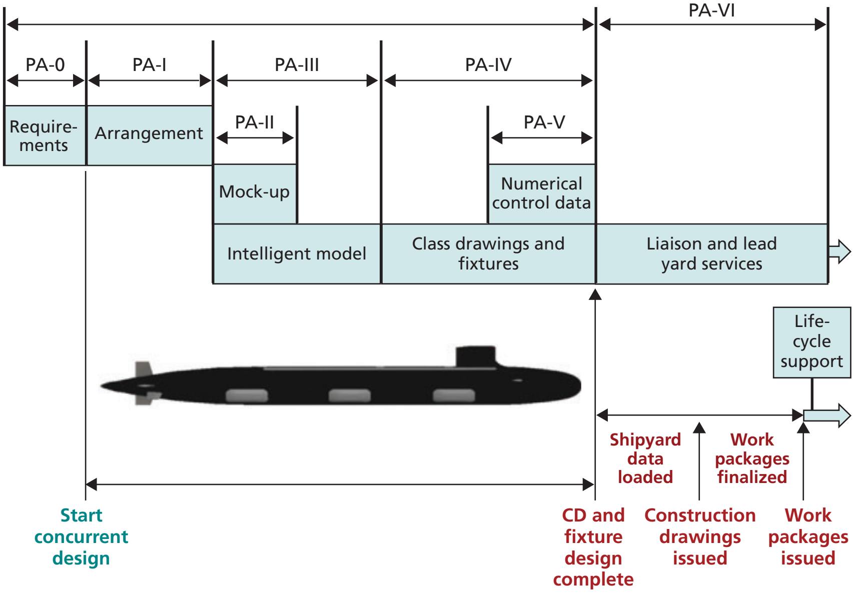
RAND *MG1128/2-5.1*

vals between design phases delayed the process and often resulted in changes to requirements or preferred approaches to a design solution.

The IPPD process was concurrent and seamless in nature. All the tasks in the traditional phases of design were still performed, but they were performed in a parallel manner, with the shipbuilder and the Navy participating in all phases of the design process, from the conceptual phase through delivery of the submarine. The IPPD process starts with a systems definition phase, followed by an integrated design/construction planning development phase. This change is a result of the desire to better integrate design and production planning while ensuring that the life cycle of the platform is considered at every stage of development. The new process led to design completion much earlier than in the traditional process.

In the new process, design phases were replaced by six product areas, which correspond to the various design products produced as the design matures (see Figure 5.2). The product areas can be thought of as design phases; however, the sequence of events is more streamlined because there is some overlap between product areas. The product areas are as follows:

Figure 5.2
***Virginia*-Class Design Process**



SOURCE: Electric Boat.
RAND *MG1128/2-5.2*

- Requirements product area (PA-0). Establishes characteristics of the future platform are established, e.g., shock and survivability requirements.
- Arrangement product area (PA-I). Turns the specifications into two- and three-dimensional drawings after the requirements have been established. Models the submarine's systems and subsystems within the ship structure to evaluate arrangements. Engineering analysis is performed and multiple design/build teams meet to identify possible design conflicts.
- Mock-up product area (PA-II). Creates mock-up drawings for limited areas of the submarine after the arrangements have been established and appropriate approval has been granted by the Navy for the design to proceed.

- Intelligent model product area (PA-III). Reviews system integration, performs interactive engineering analysis, and approves the intelligent model to gain final approval of the design configuration. These tasks add "intelligence" to the model by defining material, parts, and so forth.
- Class drawings product area (PA-IV). Produces class drawings and provides manufacturing support data for construction activities after the mock-ups and product definition are approved.
- Numerical control/manufacturing support data product area (PA-V). Develops work package design data.
- Liaison and lead yard services product area (PA-VI). Finalizes work packages and issues drawings for construction.

EB's decision to use the new process was made with government involvement and concurrence. Since the *Virginia* would be built with a partner shipyard, it was important that both shipyards were equally vested in the new process. The IPPD initiative required the government and Newport News to alter their processes during *Virginia* construction to mirror those at EB. Also, unless mandated by the Navy, no substantial restructuring of contractor organizations and vendors could be expected to take place.

During this review, EB and Newport News collaborated in nine trade-off studies on size and operating depth for the *Virginia* class. The studies, which were conducted between 1989 and 1992, also included key stakeholders–operators, builders, and industry partners. This collaborative effort became known as the design/build process.

The most important result of these studies was that the Navy and EB decided to revise the submarine shipbuilding process so that it was a cooperative process in which they were both focused on the same outcome—cost reduction without quality degradation. Principal elements agreed upon were the following:

- The EB-driven IPPD process would be cost-focused and metrics-based.
- The Navy, as the design and technical authority, would be fully and continuously engaged.

Prior to *Virginia*, submarines were designed under Navy contract by a shipyard's design division. After government approval, the designs were issued to the construction shipyard as GFI. Construction input into the submarine design process was not formalized. For competitive programs, shipyards withheld construction process information from a competitor's design organization to preserve their perceived competitive advantage. As a result, the Navy was faced with potential construction cost increases resulting from design changes requested by both the construction yard (process needs) and the Navy (requirement changes) during actual construction. In the case of *Virginia*, where the design/build imperative was cost reduction, the first issue would be the infusion of construction process knowledge and considerations into the design process.

Thus, the IPPD process for the *Virginia* opened the design process to all stakeholders throughout the submarine's life cycle; that is, from initial operational requirement generation through design and construction to delivery. This included operators (the fleet), suppliers (vendors), designers, those in the production trades, cost engineers, purchasers, engineering analysts, testers, quality assurers and naval architects. Contrary to prior ships, *Virginia* had a lean design/manufacturing process that was based on maximizing stakeholder input, simplifying the design, reusing design data, and reducing the number of parts on board the ship.

Roles and responsibilities were clearly assigned—from leadership and management through planning and detailed scheduling, design and engineering, operations (construction, test and producibility), materials, engineering finance (measuring performance to cost and managing program budgets), and life-cycle support. In effect, the new process immediately and permanently changed the prior design-construction paradigm and broke down the wall between designers and other (fleet, construction yard, vendor) inputs.

In breaking down the design barriers, EB emphasized that the opportunity to capture many of the major cost benefits would occur during the early stages of design. Further, because of the *Virginia's* equipment density, the cost and schedule penalty for disrupting the design process (for example, altering the submarine internal machinery arrangement) increased as the design process matured.

To further emphasize the objective of cost savings, the Navy program manager emphasized at the outset that elegance is simplicity, and nothing would be off limits. Design goals then became simplifying both the design and the construction processes. Ship specifications were examined for cost-reduction potential. Importantly, the design was transformed from GFI to a cost reduction–focused design in which both design and construction sides and the government were now vested.

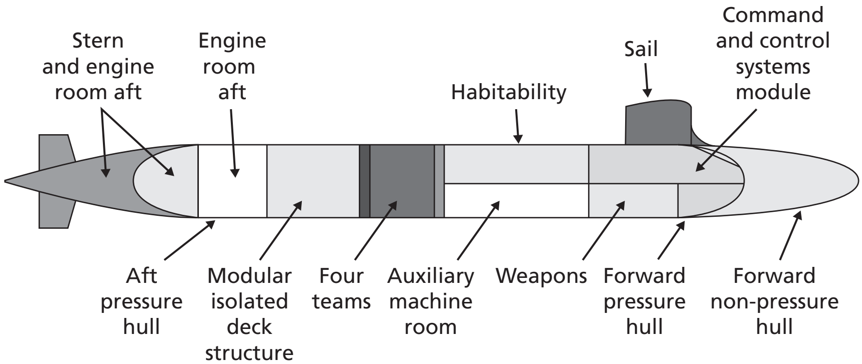
The shipyard was sensitive about its labor history. Before implementing the new process, EB met with the union leadership to lay the groundwork for a cooperative, idea-sharing relationship during the design and construction of *Virginia*. With the help of a consultant, the shipyard began to change its culture in earnest, as designer skill requirements were redefined for the *Virginia* program and construction workers were integrated into the design process.

The development of the design with the active participation of construction personnel integrated the construction processes and methods into the design base. As a result, the program achieved one of its cost-savings goals—the lead ship for the *Virginia* class was built with efficiency close to that of the third ship in a class.

Both the Navy and the shipyards were particularly sensitive to the deficiencies of the *Seawolf* program at the outset of the *Virginia* program. Thus for example, a design control method was immediately emplaced that created strict control over the introduction of new parts into the design of *Virginia*, thereby avoiding the parts proliferation that had been the case on *Seawolf*. On *Virginia*, the application of this lesson resulted in one-fifth the number of unique parts as on *Seawolf,* a proportional reduction in administrative costs for purchasing and storage during construction, and a commensurate reduction in life-cycle spares requirements.

The submarine is a system-dense military vessel. Each submarine consists of several compartments and hundreds of electrical, mechanical, and electronic systems distributed throughout and between the ship's many compartments. On prior ships, the Navy had encountered

Figure 5.3
***Virginia*-Class Major Construction Areas**



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difficulties both in system and compartment (module) interfaces. In focusing on cost control, EB decided very early to divide the ship into manageable integration challenges. Again, the reasons were simplicity, efficiency, and cost control. Integration difficulties during construction had traditionally meant design reissue and possibly rework. In both cases, cost was affected, since rework is the most expensive labor cost during ship construction. Therefore, *Virginia* was divided into major areas as shown in Figure 5.3.

Each major area team (MAT) had two co-leaders. Each MAT was responsible for its area and the interfaces with other areas, from design through delivery to operations and eventual disposal. The team was made up of "core" groups of designers, engineers, vendors, environmental and logistics specialists, and a computer-assisted design (CAD) operator for arrangements (piping, structures, electrical, and mechanical). Each MAT had a space manager, a Navy program management representative, and waterfront team members—manufacturing engineers, materials, planning, steel trades, sheet metal, electricians, machinists, and so forth. Because of manpower limitations, specialists were likely assigned to more than one MAT.

While MATs ensured major area design integration and a focus on the downstream construction process optimization and costs, system integration teams (SITs) provided design and construction continuity and expertise for specific systems or technical discipline bases that run throughout the ship (such as hydraulics, trim and drain, electrical distribution, or the ventilation system, which run the length of the ship). SITs also helped ensure cross-MAT communication within disciplines, avoiding the bulkhead and boundary conflicts and discontinuities that had been present in prior classes. EB had previously examined several different IPPD organizational approaches. Since the shipyard, as the material expert, was responsible for the cost, schedule, and performance of the product, the Navy supported the shipyard's organizational decisions. In addition, the Navy was responsible for communicating its viewpoint clearly and continuously. The Navy mirrored the shipyard team structure within the program office but had fewer team members. This approach, which placed Navy and shipyard opposites routinely in communication with each other, helped maintain consistent program focus.

The inclusion of vendors was important to the new cost-reduction-focused *Virginia*-class process. The *Virginia*-class submarine had more than 2,600 suppliers in 46 states. The program objective of saving cost without compromising performance had to be extended to the vendor level. Throughout the design process, vendor supplied components were reviewed from a cost-versus-characteristic viewpoint. The design process, which included both the design authority (the Navy) and the fleet, allowed prompt arbitration of questions regarding the cost benefit trade-off for questionable and costly system or equipment features.

Software Tools

The *Virginia* was designed entirely by computer using CAD 3-D (CATIA IV) modeling software and the Integrated Design Manufacturing System. With the CAD system, engineers built and rebuilt the ship with hundreds of iterations. All of the prototypes for the *Virginia* class were done electronically, with the exception of a select few compartments where physical mock-ups were made due to a high level of component density or personnel interaction.[14] Using CAD 3-D software has a number of benefits. Among them is the discipline it imposes

[14] These were the reactor compartment, the sail, and the lock-out trunk for the SEALS.

in the change process because of the expense to go back and re-design with CAD. Only two people, the design supervisor and the MAT leader, could approve changes to the electronic model. CAD software also provided accuracy control for the modular design/build process.

However, the CATIA IV software used by the *Virginia* program was a drawing-based system rather than a parts-based system and lacked a multi-hull capability. This was highlighted as a problem during the first maintenance availability for *Virginia*. Because the program showed drawings only for the hull currently under construction, maintainers had to manually follow a paper trail to accurately develop work packages for previous hulls. Having a parts-based design tool would minimize post-processing of data and allow builders and maintainers to access work packages electronically versus manually.

Also, designers noted that the CATIA IV software program did not have the server capacity to handle peak manning requirements. This forced EB to go to a second shift in order to maintain the design schedule until they could address the server capacity issues.

Another tool which had proved beneficial for process control in

Table 5.2
Percentage of Build Completion for Various Programs

Program	Percentage Complete Upon Pressure Hull Close
Los Angeles	33
Ohio	48
Seawolf	57
Virginia	81

SOURCE: Young, 2003.

the *Virginia* program was a software tool that had been developed by the Naval Nuclear Propulsion Program's Bettis Atomic Power Laboratory for joint alignment. After obtaining the program from Bettis, EB rewrote the specifications so that by swiping a barcode on the work package a shipyard worker would be told if he had the proper qualifications for the work involved. The barcode also held information about the parts in order to allow the qualified worker to receive parts from the material issue point. This software also provided objective quality control evidence.[15]

Modular Build

The modular build process that had been introduced in the *Ohio* program and used for the *Seawolf* program had been improved and allowed many of the components to be built and tested prior to being loaded into the hull cylinder. For example, early on in the construction sequence, the *Virginia*'s Command and Control System Module was built, tested, and rated by OPTEVFOR at a land test site prior to being inserted into the hull. Module-to-module interfaces were controlled through the Accuracy Control Plan and use of photogrammetric and laser trackers to identify the attachment points.

The first *Virginia*-class ship was 81 percent complete when the shipyard closed the pressure hull, compared with 57 percent for the *Seawolf* and 33 percent for the *Los Angeles* (see Table 5.2). Three years into construction, 99 percent of the *Virginia* drawings had been issued versus 65 percent for *Seawolf.* In addition, there were 80 percent fewer trade-identified design errors (12,000 changes versus 70,000 changes) in the *Virginia* compared with the *Seawolf.*[16]

As the *Virginia* program progressed, industry managers sought to increase the size of the modules and reduced the number of separate modules from ten to four. This strategy required some up-front transportation and infrastructure investment in order to be able to move heavier modules between EB's yards in Groton and Quonset Point and Newport News's yard. On the back end, however, by increasing

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[15] The lack of similar software at Newport News may have contributed to some of their weld difficulties.

[16] Interviews with industry.

module size the shipyards could reduce shipyard construction time and thus decrease fixed overhead costs.[17]

The *Virginia* program benefitted from the fact that the original design contract had also specified that EB would be the construction yard; thus, the initial design effort was specifically tailored to EB's processes. Some of the submarine design had been completed by EB before the teaming arrangement was initiated. This required EB designers to rework the design to account for different construction techniques at Newport News, setting back the time line 14 months to work out shipyard differences. In addition, the major reduction in submarine construction after 1991 foreseen by EB allowed the shipyard to focus its processes on the upcoming downsizing and to shift labor to Quonset Point, thereby benefitting from more-flexible craft jurisdiction rules and lower composite labor rates.

Newport News sent a team of 35 engineers to work with EB in Groton on the design/build team to identify and accommodate different build practices in the final production plan. Industry and Navy representatives suggested that if future submarines were going to be jointly built between the two yards, they would also need to be designed jointly to efficiently execute the design/build process.

The shipyards used an integrated master schedule (IMS) for *Virginia's* design/build process, which was a change from the *Seawolf* program. With over 35,000 elements, there was a high level of detail built into *Virginia's* IMS, and it required a commitment of 35 people over two months to prepare. The *Virginia* program moved production planning funds that were budgeted for the subsequent ship construction line item up to the earlier design item to account for these early planning costs.

The IMS enabled early decisions on component placement and construction timing and allowed managers to build parallel paths between component and system development into the schedule. As a simple example, in *Virginia* the construction schedule for the Auxiliary Machinery Room module required the tanks to be in place before the

17 O'Rourke, 2008a.

pipes were put in, so the tanks were put into the design schedule before the pipes.

Managers also used the IMS process to impose discipline and "lock in" delivery dates for both CFE and GFE. Of particular concern in the schedule are components or systems that use developmental technologies. These impose a high level of schedule risk and thus the schedule must accommodate "off-ramps" and a "plan B" for new technology.

The build strategy was initially embedded in the design developed by the 15 active MATs that together covered the entire ship. EB found that these MATs were too large and sometimes difficult to coordinate, so for the SSGN conversion, it broke into smaller teams and prioritized spaces from 1 to 35.

Metrics and Oversight

Because of the problems with the *Seawolf* program, the fraction of initial design completion at the start of construction became a key performance metric for EB and the Navy. The implementation of the concurrent engineering/IPPD process on the *Virginia* put the ship more than 2.5 years ahead of *Seawolf* in the fraction of drawings issued at a comparable time relative to construction start. Furthermore, construction of the *Virginia* began with the electronic 3D product model essentially complete and ten times as many construction drawings complete—50 percent, compared with about 5 percent for *Seawolf*. Importantly, because of the design disclosure facilitated by the new process, the Navy's process for reviewing the formal drawing had been dramatically lightened compared with prior-class ships.

During the 1980s, U.S. submarine construction programs had been criticized for both poor schedule performance and cost accounting. As a result, the *Virginia* program decided to shift to an Earned Value Management System (EVMS) as the cornerstone program performance measurement system. Rather than the prior method, which essentially compared planned results with actual results, the earned value method integrated cost, schedule, and scope to help anticipate future performance and allow the program manager to identify and control problems while they were still manageable.

The *Virginia* program manager used the EVMS with cost performance indices (CPIs) and schedule performance indices (SPIs) to monitor project performance. EVMS was closely tied to the budget and the construction schedule to ensure the dependability of the metrics. CPI or SPI variance is a major indicator of trouble in a program, but for these metrics to be trusted, the baseline needs to be built with realistic budgets and the correct sequence of events. These metrics were reviewed at weekly meetings and problems were highlighted early on. Also, independent means of validating the CPIs and SPIs, such as the virtual ship model and construction oversight by the SUPSHIP, were deemed useful by the Navy.

While it is true that earned value management is helpful from the viewpoint of schedule enforcement and SPI, it was also important that the schedule was properly baselined, tied to the budget, and built to adequate detail while having buy-in of both design and operations (trade) managers, who would be expected to execute the design and the schedule.

On *Virginia*, despite its drawbacks, CAD had a significant advantage, since a ship could now be built and rebuilt with several (indeed hundreds) of iterations in order to properly design the ship and plan construction. CAD also allowed *Virginia* design and production linkages to be readily clarified. A broader range of participants could enforce design control and develop requirement, technical, and production process comfort with the design by means of design "lock-in."

For example, piping configurations were correlated with fixture and hanger plans. The design authority, technical authority, trade representative, and Navy shipyard representative were all design participants; this allowed both the construction manager (shipyard) and the Navy to enforce close design control after design lock-in, thereby cutting the cost of design changes, a prior problem.

The *Virginia* CAD system was used to develop the manufacturing assembly plan (MAP) with greater ease; therefore, an integrated master schedule was also more readily developed. During the design phase, metrics were selected that were appropriate to that phase of the design/build process. In the design phase, items such as the following were tracked:

- drawing type completion versus schedule
- work package/assembly plan production versus schedule
- special instruction packages completion versus schedule.

Each ship hull, mechanical, and electrical design drawing subset in the *Virginia* was assigned to an engineering director, scheduled in detail for completion based upon the IMS, then tracked and managed. Examples include

- hull: e.g., ballast tank/fairwater completion versus schedule
- mechanical systems: e.g., propulsion/ventilation/trim/drain/hydraulic systems drawing completion versus schedule
- all electrical systems: e.g., AC/DC, normal/emergency, main/auxiliary electrical distribution drawing completion versus schedule.

Not only did design scheduling take place at the system drawing level, the production side was also addressed during the design process as well. Each work package was scheduled for completion, and every jig and fixture needed to support construction was also scheduled for design and production. *Virginia* arrangement activities were taking place initially at rates up to 750 per month, and soon about 300 mock-up drawing development activities were in progress per month. At their peak, about 200 intelligent model development activities were taking place. At the same time, *Virginia*-class drawing activities were averaging about 1,200 per month. In addition to shipyard or prime contractor detailed scheduling for SPI calculation purposes, vendor equivalent monitoring took place to allow EVMS inclusion so that no vendor delinquency issues arose.

During *Virginia* construction, system design and engineering were the responsibility of the Director of Engineering. The MAP was the basis for assigned system target dates during the design/build process. Subsets such as ventilation and nonnuclear piping were allocated to group supervisors. The responsible group supervisor proposed the design/build schedule and received a budget allocation that coupled cost and system schedule. Weekly *Virginia* design reviews were followed within 24 hours by problem, action item, and deliverable status reviews by the shipyard construction manager with problem corrective actions directed immediately. "Virtual" shipyard progress review meetings were held weekly with Navy and vendor participation. Applicable system design engineers represented their systems as needed at meetings. Virtual system mockups allowed fine-grain system design review and saved both time and overhead (travel) cost.

Three years into the *Virginia* program, the initial requirements remained unchanged despite challenges. In each case, the Navy program manager cited cost control as the dominant program requirement in denying changes.

Systems and components were added to the virtual ship model as the system designs were being developed. A "virtual" crew was added as the ship was being designed to test for equipment access and operation. Nonetheless, actual physical mockups continued to be used as design verification devices where a high degree of human interface was the case, such as in escape trunks.

Construction phase metrics naturally differed from design phase metrics. The starting point for construction was material ordering; thus, the metric of interest was material on hand versus planned. Material issue versus time then provided a follow-on metric and was an indicator of impending construction activity.

Construction metrics covered the complete range of ship construction activities down to the ship system level. Module construction, preparation, outfitting, and joining versus plan and individual system completion progress through compartment turnover was monitored for each ship system. For example, a mechanical system metric started at the basic level of piping joint completions versus time and progressed through system test completion rates.

On a higher level, ship compartment joining versus plan and key event dates, and compartment inspection progress and turnovers to the Navy versus plan were also tracked closely.

Naturally, electrical distribution systems had similar, parallel system completion metrics and SPIs. This included cables in place, connections made, and continuity and system operational tests complete versus plan. Throughout the construction process, the cumulative system construction progress provided SPIs and CPIs. Although the data provided by EVMS were after the fact, EVMS nonetheless permitted *Virginia* design/build to be managed to more rigorous schedule and cost standards than prior ships.

During the *Virginia* program, issues arose when separate shipyards tracked their own data offline, making it difficult to track progress. SUPSHIP Newport News and SUPSHIP Groton both had independent baselines but also had interface control in order to monitor overall progress. The shipyards and SUPSHIPs sought to resolve problems at the lowest possible level and the majority of problems were addressed at the industrial site. When issues were identified, the engineers would analyze the problem and propose a solution, and SUPSHIP would approve or disapprove the change on the spot.

Areas of Cost Growth and Schedule Delays

In 1998, the GAO identified some reduced capability subsystems that were experiencing developmental problems.[18] Program management decisions and internal funding cuts for the program led to modifications to the acoustic intercept system and electronic warfare system and reduced performance capabilities for these subsystems. Areas where developmental problems were emerging included the propulsor, external communications systems, and the towed array. The initial propulsor design did not meet the program office's design goals; as a consequence, the Navy developed two alternative designs for testing. At the time of the GAO study, the Navy had not yet developed a formal operational requirements document for the external communications system, so the design had not been finalized. Additionally, the existing TB-29 towed array system had been deemed too expensive, and the Navy was looking to procure a new array.

By FY00, the *Virginia* program had avoided the prior program cost overruns, program cost was within 8 percent of budgeted cost, and program cost performance was within 2 percent of target. In October

[18] GAO, 1998.

2004, the first-of-class was delivered to the Navy four months past the scheduled delivery date, compared with the 25-month delay for the first *Seawolf* and the 19-month delay for the first *Ohio*.

Newport News also experienced cost growth of approximately 50 percent and a schedule delay of almost a year in delivering the second *Virginia*-class submarine, the USS *Texas*. Much of this cost growth and schedule delay was due to the ten-year hiatus between the delivery of its last *Los Angeles* submarine, the USS *Cheyenne*, and the *Texas*. Although its submarine workforce stayed employed by working on aircraft carrier construction, there were some learning pains involved with the transition back to building nuclear submarines. Subsequent *Virginia*-class boats built by Newport News have seen some cost growth or schedule delays.

Despite efforts to reduce costs, the GAO found that many program costs had been underestimated at the outset of the program.[19] The following cost growth drivers had been identified by 2005.

1. Increases in labor hours accounted for 40 percent of cost growth:
   a. integration issues between shipyards
   b. material not arriving on schedule, leading to worker inefficiencies and additional overtime work
   c. a union strike at one shipyard that affected productivity, causing disruption and resulting in four pay increases totaling $3.10 per hour.
2. Material costs accounted for 43 percent of cost growth:
   a. budgeted funds not supported by current vendor costs—the Navy predicted a 20 percent increase in material costs, but actual increase was closer to 60 percent
   b. diminished supplier base for highly specialized material (due to lower production rates)
   c. lack of design maturity for certain electronic components
   d. full funding of ships in the year of authorization (block-buy contract).

[19] GAO, 2005.

3. Navy-furnished equipment (radars, propulsion equipment, and weapons systems) caused 14 percent of cost growth:
    a. ship construction funds
4. Ship overhead (employee benefits, shipyard support costs and labor rate increases) accounted for 3 percent of all cost growth:
    a. health care and pension costs rose faster than anticipated
    b. anticipated production of two ships per year did not materialize.

The final cost of the first hull was $2.8 billion (FY05) versus the $1.8 billion (FY05) COEA estimate.[20] Some of this opportunity loss for cost reduction was ascribed to lack of economies of scale while at low-rate production of one ship per year (each yard building one-half of a ship per year). With the government's desire to take cost out of the program and the shipyards desire to increase production, the government instituted a contract incentive for follow-on ships. This incentive, sometimes known as the "2-for-4-in-12," would increase the production rate to two ships per year if the shipyards could get the total program cost down to $4 billion ($2 billion per ship in FY05 dollars) by 2012.

The *Virginia* program achieved these cost savings through increased production volume, but also through better performance in key areas. On the labor side, the shipyards were able to take about 100,000 man-hours out of the construction by simplifying materials and designing in more automation. For instance, designers at EB redesigned some products to use laser-cutting methods. The shipyards did not question the requirements for the most part but looked for ways to deliver capabilities in a way that would reduce costs. For example, instead of 12 smaller vertical launch missile tubes on each platform the designers proposed two bigger tubes that would offer the same (or greater) capability with less cost.

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[20] The COEA estimate in FY95 dollars was $1.5 billion. We used Naval Center for Cost Analysis SCN inflation indices to convert the FY95 dollars to FY05 dollars.

Life-Cycle Issues

Life-cycle costs extend beyond the production cost for the program. These costs include operating costs (fuel, payload and personnel), maintenance, modernization, and disposal costs.

Early on in the design process for the *Virginia* program, the teams brought in a number of stakeholders to recommend life-cycle design considerations. Designers consulted with disposal and dismantling technicians on both materials and arrangements. Operators and maintainers walked through virtual mock-ups to validate human interfaces.

Virginia was originally designed to maximize operational availability by minimizing the need for preventive maintenance in the first four years after delivery. After delivery, EB was contracted as the Navy planning yard for the *Virginia*-class submarine. As planning yard, EB was contracted to assist in life-cycle sustainability of the *Virginia* class; this included reducing ownership costs, providing quick response to fleet problems and support services ranging from alteration conceptualization through design resolution, integration, installation, testing and ship design configuration maintenance. In addition, EB provided advance planning and design/engineering for overhauls and repair availabilities.

As the planning yard, EB has continued to investigate ways to "design for affordability" through redesign. Designers replaced the original sonar sphere with a hydrophone array. The original design required 1,000 transducers, each of which had only a 17-year life. The hydrophones in the new array not only were less expensive to produce, but also had a lifespan equal to the submarine's expected 33-year lifespan.[21]

One of the limitations of the CAD tool used for the *Virginia* program is that it only shows the configuration of the current hull under construction. This was identified as an issue in the first availability of USS *Virginia*. It is expensive to go back into the electronic product model and add "as-built" and the funding for this is typically not available in the design/build contract. New drawings were issued for com-

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[21] Jones, Kronenberg, and Scherer, 2009, p. 4.

plex electrical systems for safety reasons, but other drawings changes were not a priority for the shipyards at the time of delivery.

Lessons from the *Virginia* Program

The end of the Cold War and concerns over the cost of nuclear submarines forced the Navy and the shipbuilders to take a different approach to the conduct of the *Virginia* program. Both sides realized that designing and building a lower cost submarine that was responsive to the new threat environment was imperative for the survival of the program, and to a large extent, to the nuclear submarine industrial base. Learning from the *Seawolf* program and remembering the lessons from earlier submarine programs, the *Virginia* program sought to reduce risks by using the best technologies available while constraining the development of new technologies.

Some of the *Virginia* lessons mirror those of the *Ohio* and *Seawolf*: Use a single design/build organization, have an appropriate level of design complete before construction starts, obtain congressional and DoD support for the program, and maximize the degree of modular construction to reduce build costs. Other important lessons are detailed below.

Decisions during the design of the submarine are critical to program success. For the *Virginia*-class submarine design and construction, the Navy concluded that the key to cost-efficient nuclear submarine construction lay in the design phase. This provided an early opportunity to maximize savings by emphasizing such policies as component standardization and commonality, design simplicity, and design cost consciousness in an IPPD framework. Further, it had become clear that for costs to be reduced, cost reduction had to be established as the basis of all program decisions, with clear authority for both program execution and design decisions.

A cooperative and interactive contracting environment must be established. The Navy established a contracting and acquisition environment that fostered a level of cooperation and involvement between the Navy and the shipbuilders that had not been possible in the past. Relationships between the Navy and the shipbuilders turned from adversarial to collegial and the former rivalry between Newport News and EB was transformed into an effective teaming arrangement. The agreement to equally share profits between the shipbuilders encouraged the sharing of ideas to reduce costs. The incentive of building two submarines per year further drove the shipbuilders to achieve the necessary cost savings.

Requirements must be held constant to the degree possible. Earlier programs showed the cost and schedule impact of changing requirements during the design and build of the submarine. The *Virginia* program exercised stringent configuration control and greatly reduced the number of change orders during the build of the lead ship in the class. This control over requirements changes helped the program deliver the first-of-class with less cost and schedule growth than experienced in previous programs.

The advantages and disadvantages of different design processes must be understood. Realizing that its future depended on the success of the program, EB not only reshaped its size and structure but adopted a new design philosophy for the *Virginia* program. A parallel, concurrent design approach in an IPPD environment replaced the lockstep sequential design process of the past. The design teams included not only draftsmen and engineers but also knowledgeable people from the construction trades to ensure that the design was buildable with minimum changes. The Navy was also an active member of the design team, and frequent review sessions were held with all stakeholders to ensure that the design was understood and agreed to by all.

An integrated master schedule must be established, monitored, and executed. In the *Virginia* program as never before, a detailed IMS was established early in the program and bought into by all key participants. The IMS was relentlessly monitored for execution, compliance, and decision follow-up. The design drawings were largely complete before construction started. These and other cultural changes resulted in arguably the most successful construction program in U.S. nuclear submarine history.

There must be strong and experienced leadership in both the Navy and the industrial base. Part of the success of the *Virginia* program was due to the strong leadership and management in both the Navy and at the shipbuilders. The Navy's philosophy of identifying promising young submarine officers early and directing them through a career path that provided knowledge and experience resulted in the leaders that were needed in the challenging environment. The leaders at the shipbuilders had also risen through the ranks and understood what was needed for program success.

CHAPTER SIX

Lessons Identified

Much has changed in the Navy's nuclear submarine environment in the 35 years from the start of the *Ohio* program to the current status of the *Virginia* program. The *Ohio* and *Seawolf* programs began in a period of heightened tensions between the United States and the Soviet Union, each pushing technology and force structures in an attempt to gain an advantage over the other. The end of the Cold War brought a change in operational focus, from countering the Soviet threat in the oceans of the world to the world of terrorism and the need to operate in the littorals. The *Virginia* program faced this new operational environment.

Available budgets for nuclear submarines mirrored this change in operational focus. The end of the Cold War brought a call for a "peace dividend" and a reduction in force structures. The Navy's force dropped from more than 100 submarines at the end of the *Los Angeles* program to approximately half that number today. Civilian policymakers (including DoD) and the Navy realized that the costs for new submarines in the post–Cold War era would have to drop significantly in order to support desired force structures.

The industrial base also faced turmoil during the period from the *Ohio* to the *Virginia*. The large procurement years of the *Los Angeles* submarines led to competition and intense rivalry between EB and Newport News, the two shipyards that build nuclear submarines. Both shipyards had large workforces at the start of the *Ohio* program. Workforce demands at both shipyards dropped significantly with the termination of the *Seawolf* program. Newport News was able to sustain a fairly large workforce to support new aircraft carrier construction and the midlife reactor refuelings and major repair of in-service carriers. However, with submarines as its only product line, EB was forced to remake itself and significantly reduce its workforce in order to survive. Once heated rivals, the two shipyards now partner equally in the construction of the *Virginia*-class boats.

Lessons were certainly identified from the *Ohio* program in many areas, including setting operational requirements, pushing existing technologies, and interacting with the industrial base. Unfortunately, some of those lessons were not actually "learned" during the conduct of the *Seawolf* program. For *Ohio*, the Navy used the best of existing technologies wherever possible, choosing to push technology limits in only a few areas. *Seawolf* aimed for significantly greater operational capabilities compared to existing SSNs to counter gains in Soviet technologies and capabilities. Technology was pushed in many areas leading to a greater risk and higher cost program. The Navy utilized a relatively simple and straightforward contracting relationship with a single shipyard for the design and construction of the *Ohio*-class submarines. The acquisition strategy for *Seawolf* changed to each shipyard designing different portions of the submarine and designing in a way that the submarine could be built in either shipyard. This led to additional efforts to integrate the design teams and construction practices at each shipyard and to negotiate the differences that ultimately arise from such a design relationship.

The *Virginia* program, reacting to tighter fiscal scrutiny, did seem to learn from the *Seawolf* program. It used the best technologies available and was careful to control technology risk and cost. It also returned to a single shipyard design/build agent, simplifying contracting relationships. The shipyards also learned from the *Seawolf*, or, in the case of EB, adapted to the new environment. Reducing cost became the mantra for both the Navy and the shipyard. When Congress requested that both shipyards compete for construction contracts, EB and Newport News, with encouragement from the Navy, reacted in a novel way: They decided that partnering as equals was better for them and the *Virginia* program than competing as adversaries for limited workloads. In addition, EB and the Navy recognized the merit of a complete review of the technical lessons learned in the *Seawolf* program before beginning the next submarine development program.

All three programs had tenuous beginnings. There were cost overruns and schedule delays in the construction of the first-of-class in each program. The *Ohio* and *Virginia* programs made corrections, and both are typically viewed as successful. *Seawolf*, likely due to the changing threat and budgetary environment, was terminated before changes could be made to correct early missteps.

Overall, the submarine programs seem to be effectively managed, largely due to a rigid discipline that grew from the philosophies of the Navy's nuclear reactor programs. Also, the Navy's historical approach of assigning "front runners" as program managers has helped ensure aggressive, solution-focused management teams.

There will be challenges in the future for both the Navy and industry as a result of changing operational requirements in response to threats and fiscal conservatism due to constrained budgets. The managers of new submarine design and acquisition programs must not forget the lessons of the past while adapting to future demands and constraints. The lessons listed below draw on the experiences of the three previous programs while postulating how managers must react to the future environment.

Lessons are appropriate at two levels—the relatively short-term, narrow focus of a specific program and the long-term, future strategic vision of the Navy for the force and industrial base. To be useful, lessons should be categorized along different dimensions, although many lessons run through whatever categorization is used. We first describe the lessons at the strategic level and then list the lessons at the program level in terms of the overall support and management of the program, the impact of operational requirements on technology and risk, the contracting format and relationships that are established, the design and build of the submarine, and the planning for the ILS of the submarines.[1]

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[1] Although the lessons are drawn from submarine programs, they are also appropriate for surface ship programs.

One overarching lesson from the three programs is the importance of program stability. Stability applies in many areas—consistent funding, a long-term build strategy, fixed operational requirements, stable and capable program management, and an integrated partnership between the Navy and the shipbuilders. Program stability is not sufficient for program success, but it certainly is a necessary attribute that greatly contributes to the success of a program. The lessons that follow largely address ways to achieve program stability.

Top-Level Strategic Lessons

The top-level strategic lessons that we outlined in Chapters Two through Five are global in nature. They are applicable for the PEO for Submarines and for senior Navy management. These strategic lessons address the overall management of the nuclear submarine force and of the industrial base. They cover growing informed future program managers, interacting with OSD and Congress, managing the total submarine force including the maintenance and modification of in-service submarines, and interacting and shaping the nuclear submarine industrial base including the private shipyards, the vendors that support submarine design and construction, and the public shipyards that maintain in-service submarines.

Successful programs involve having the experienced technical and programmatic leadership continually at the helm. This requires a strategy to grow people so they are experienced in various disciplines. Growing future program managers must be planned and implemented far in advance of any specific program. The Navy has been successful in identifying promising officers early in their careers, sending them to gain additional education in naval architecture, program management, and other related disciplines, and assigning them to ongoing programs at a junior management level. In general, the leaders of today's submarine programs have had advanced education and have "earned their stripes" through experiences on previous programs. The Navy must continue to plan on growing the right levels of expertise in the right people, sending them to various operations- and acquisition-related positions, as well as providing appropriate education in the academic community. This will be difficult in the future because there may be fewer programs for assigning young officers, and force structure reductions may lead to a smaller pool of nuclear submarine officers. It is therefore important that the Navy identify the most promising junior officers for future management positions and provide learning experiences for them. Equally important for program success is the civilian leadership in the various Navy technical organizations and laboratories as well as the leadership in the private sector.

There should also be continuity in the management of new programs. Changing leadership during the program can cause changes in goals and management strategies that could be detrimental to the success of the program.

The Navy must take a long-term strategic view of the force and the industrial base that emphasizes flexibility, adaptability, and availability. A specific program is only one step in a successful military capability and the industrial capacity to provide and support that capability. The Navy must take a long-term view and understand how a specific program nurtures and feeds the overall strategic plan. A key lesson is that a new submarine development program produces more than a strategic military asset; it also contributes to domestic economic goals and is one part of a long-range operational and industrial base strategy.

A new submarine does not remain static once it is delivered to the force. Technologies change, new capabilities are needed, and new threats emerge and evolve. These future evolutions require the need to maintain a technology and capability edge and to update existing platforms with new technologies and new capabilities. The improved *Los Angeles* class, the conversion of the *Ohio*-class SSBNs to SSGNs, and the construction of the USS *Jimmy Carter* are three examples of how original designs were modified for new missions and capabilities. At some point, new classes of submarines must be designed and constructed.

The technical community and the industrial base that designs, builds, and maintains the fleet must be sustained so they can provide the required capabilities when needed. The technical community includes the Navy engineering directorates and the laboratories, test centers, and centers of excellence that support nuclear submarines. These must be staffed and funded to provide needed technical inputs when needed in a cost-effective manner. Recognizing the need for a strong engineering capability within the Navy, the engineering and technical staff at the Naval Sea Systems Command (NAVSEA) is now starting to grow after a decade of staff reductions.

The design personnel and facilities at the two private shipyards must also be sustained and challenged so they can support future submarine design efforts. Funding and supporting concept studies for evolutions of existing platforms or the development of new classes of submarines is needed to sustain and nurture these key design resources. These efforts should go beyond the two shipbuilders to include the major vendors that support nuclear submarine design and construction. The history of past programs reinforces the need to maintain a healthy supply base, especially in the nuclear submarine community, where many skills are unique and cannot be supported by surface-ship programs.

Supporting and Managing the Program

Future program managers must "manage" from several perspectives. They must interact with the shipyards and the vendors for the design and construction of the submarine. They must also understand technologies and how the technology-oriented commands can successfully support the program. Finally, they have to manage the expectations of higher-level organizations such as the PEO, senior Navy leadership, and most importantly Congress. Effective management and support must span the life of the program, from concept to disposal. There are several aspects to a well managed and supported program, which we discuss next.

A new program must be adequately supported within the Navy, across OSD and Congress, and by the scientific and technical community. Support must be both external to the program and internal within the Navy and submarine community. Political support is most important for the advancement of a new acquisition program. Without the support of the politicians, sufficient funding may not be available to adequately conduct the program. Congressional support was important for the *Virginia* program to succeed. Support must also come from the scientific community that possess the technical knowledge needed to make informed decisions and from the public. Finally, support must come from within the Navy.

The program should be open and transparent to all and should describe both successes and problems. Proactive disclosure during the program is necessary to maintain OSD, congressional, and public support. There should be periodic feedback—at the appropriate level of detail—to senior decisionmakers and important stakeholders on how the program is progressing, especially when there are unanticipated problems. In this regard, a good media management program is necessary. Bad press can greatly and negatively affect a program. Effective communications must be proactive, not reactive, in briefing Navy leadership, OSD, and Congress. Program managers must head off bad press, not react to it. Special access provisions will be needed to share sensitive information.

All appropriate organizations, commands, and personnel should be involved in the program from the beginning. The program management and the Navy must be informed customers supported by adequate technical, operational, and management expertise. The program must have the correct composition of the right skills, people, attributes, experience, and ability to identify risks, and solutions, early and throughout the program. In addition to the technical community, the program office must involve operators, builders, and maintainers from the beginning of the program. The program manager should plan on spending the time necessary to ensure that the program philosophy and underlying principles (cost control, low technology risk, for example) are clear to all participants and emplaced at all levels. In addition, the program manager should be empowered with required decision-making authority (e.g., change control).

Setting Operational Requirements

One of the most important aspects of a new program involves the decisions made very early on the desired operational performance of the new submarine. These early requirements decisions influence the degree of technology risk for the program and affect the likelihood of program success or failure. The operational requirements for the platform are translated into performance specifications that lead to technology choices to achieve the desired performance. The operational requirements, especially the desired operational capability, also affect ILS planning.

Changing requirements during the design and build of the submarines can lead to cost growth and schedule slippage. The Navy must control to the degree possible any changes in requirements unless they are absolutely necessary.

The requirements of all elements of the integrated capability should be thoroughly analyzed to achieve an efficient and effective total system design. A submarine is an integration of the pressure hull, the power and propulsion system, sensor and communication suites, and weapon systems. Operational requirements in one area will affect design considerations in the other areas. More-capable sensor systems may require additional power and a different propulsion system, which could affect the pressure hull design. The desire for greater weapons capability with more or newer weapons may also affect pressure hull dimensions.

It is challenging to find the right balance among the various system requirements, especially when the submarine class will be in the operational fleet for 30 years or more. Operational requirements and technologies change over time, resulting in major modifications during a submarine's operational life.[2] When setting the requirements for different submarine systems, program managers must understand the current and emerging technologies in those systems, how requirements might change in the future, and the trade-offs between costs and risks (the subject of the next lesson).

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[2] The initial design of a new submarine will include margins for power, weight, and other metrics. The three programs set and maintained adequate design margins during the design and construction of the class. This practice should continue for future programs.

The *Ohio* program faced such a trade-off when setting the number and size of the missile tubes. More and bigger tubes would result in a larger submarine. Working closely with the Strategic Systems Program Office, the *Ohio* program set a requirement for a missile tube with a larger diameter than needed for the C4 missile. This decision resulted in a relatively smooth transition since the last eight submarines in the *Ohio* class were specifically built for the D5 missile. The larger missile tubes also facilitated the conversion of the first four *Ohio*-class submarines to cruise missile submarines.

A similar decision during the *Seawolf* program led to a less favorable outcome. Anticipating an as-yet-undefined future weapon that would be larger and quieter than current weapons, the *Seawolf* design include eight torpedo tubes each 26.5 inches in diameter versus the 21-inch tubes on previous classes. These larger tubes, in combination with a large weapon load, led to a much larger pressure hull than on previous classes of attack submarines. The end of the Cold War and subsequent budget shortfalls led to the cancellation of the new weapon. If there had been a threat and the budget were available to support a new weapon development program, or if there had been significantly more than three submarines in the class, the larger torpedo tubes may have proved worthwhile. However, the Navy has yet to take advantage of the larger tubes.

Program managers must understand the current state of technology in those areas that apply to their program and how a platform's operational requirements affect technologies, risks, and costs. The desired operational performance will drive the characteristics of the platform and the technologies needed to achieve the performance goals. Program managers must be supported by a technical community (as mentioned previously) that completely understands the state of those technologies that are important to the program, where needed technologies exist, and where technologies must be significantly advanced. Although it is necessary in some instances, relying too heavily on significant advances in technology can lead to risks in achieving the desired operational capabilities and in meeting cost and schedule goals. Due to the need to counter an increasing Soviet threat, the *Seawolf* program aimed for significantly greater operational capabilities than the *Los Angeles*. The end result was a new submarine design that pushed technology limits, especially in the case of reducing acoustic and other signatures.

It is important for program managers not only to know the current state of various technologies but to understand how changes to operational requirements relate to the technology levels that are available. That is, if certain operational goals are beyond the state of current technology, what operational capabilities can be supported by existing technologies? This basically relates to trade-offs between operational requirements and technological risks (and costs). Again, this is where both operators and the technical community are important during the early stages of a program. The developmental platform and the developmental combat system in the *Seawolf* led to a high degree of risk. Backing off the requirements slightly, especially with the combat system, could have significantly reduced those risks. Therefore, program managers must understand technical boundaries and the risks inherent in an evolutionary versus a revolutionary strategy. Existing systems can be scaled up to some degree. However, scaling an existing system too far leads to difficulties and ultimately results in entirely new systems or significant problems.

Program managers must understand that when they specify an operational requirement, they must also specify how to test for the achievement of that requirement. Stating an operational requirement is the first step in setting program goals. But that first step must be complemented by a plan for how to understand whether the platform meets the stated operational requirement. This typically involves test procedures—who will test, how the test will be conducted, and how success or failure will be measured. Although it is often difficult to plan for testing early in a program, it is necessary to ensure that all parties agree on the processes to measure how the performance of the platform meets operational capability objectives.

Establishing a Contracting Environment

Establishing an open and fair acquisition and contract environment is another important aspect of any program. Bad decisions here will resonant throughout the life of the program. Issues include choosing the organizations involved in designing and building the new submarine, the type of contract, the specifics within the contract including incentives, the decisionmaking process when issues arise, and the payment schedule. A number of lessons from the three programs are important for future programs. These lessons, discussed below, often overlap but aim for a fair, collegial partnership between the program office, the prime contractor, and the subcontractors.

Consider a single integrated design/construction prime contract. The *Ohio* program had one organization, EB, design and build the submarines, but had separate contracts to different EB divisions for the design and the build of the first-of-class. This led to schedule delays and cost growth to reconcile differences between the two contracts. The *Seawolf* program had the two shipbuilders each design portions of the ship with competition for building the first-of-class. Again, there were significant problems with this approach. The *Virginia* program involves a single design/build prime contractor with Newport News serving as a major subcontractor. This arrangement, plus other initiatives, has resulted in a largely successful program.

The choice of organizations and their role in a new program must reflect the status of the industrial base and policy on potential future competition for design and build contracts. Currently, there is no competition between the two shipbuilders; rather, an effective partnership has evolved. Given the direction of future defense budgets and the gaps between new program starts, it is unlikely that the Navy would desire, or could afford, future competition for new submarine design and construction. If future competition is not feasible and the nation desires to maintain two nuclear-capable submarine builders, then the Navy must encourage and foster the current partnership arrangement.

Use a contract structure with appropriate provisions to handle the technical risks in the program. The *Ohio* and *Seawolf* lead ship contracts were both fixed-price incentive-type contracts. Yet the risk-sharing was substantially different from the prior early *Los Angeles* contracts. Both had escalation provisions that covered the effects of inflation up to ceiling price and up to the contract delivery date without penalty. Both had substantially larger spreads from target cost to ceiling price than early *Los Angeles*–class contracts possessed. Extensive provision of GFE for developmental components further reduced shipbuilder risk. The agreement for the government to pay for changes to drawings (other than nondeviation ones) also greatly reduced lead ship risk for *Seawolf* and was key to obtaining responsive, competitive best and final bids from EB and Newport News.

The *Virginia* program's lead ship risk provisions took a different approach. Rather than providing the detailed design drawings (developed under a separate contract) as GFI to the construction shipyard, *Virginia* added cost-plus-incentive-fee construction line items for the lead ship to the original cost-plus-design contract. All the detailed design data were contractor-furnished and were all nondeviation. EB had every incentive to resolve design issues promptly because doing so facilitated its shipbuilding operation. This was consistent with the overall collaborative approach taken throughout the *Virginia* program, which delivered an effective lead ship very close to its original delivery date without the contentiousness that had marked earlier lead ships.

Fixed-price contracts are appropriate when there is little risk and uncertainty and when changes to the design or build are not anticipated. While the Navy can try to place all risk on the contractor by using a fixed-price contract, the Navy ultimately holds all program risk. It is far better to structure a contract in which the contractor is responsible for risks under its control (e.g., labor and overhead rates, productivity, materiel costs) and the Navy is responsible for risks beyond the contractor's control (e.g., inflation, changing requirements, changes in law). Appropriate cost-sharing provisions can be drafted to handle risks that neither party controls or that both parties have equal influence over (e.g., technology changes, acts of God, energy shortages).

Any contract, whether fixed-price or cost-plus, must have adequate incentives for the contractor to "do better." The lessons here are that (1) technical risks must be identified early, and (2) much thought must be given to deciding, with industry, the appropriate form of the contract and the incentive and risk-sharing clauses to be built into the contract.[3] Getting the incentives wrong will almost guarantee problems with the conduct of the program and the relationships between the Navy and the contractor.

The contract should specify desired performance requirements and how to test that they are achieved. Specifying performance requirements is not sufficient; how to test that the design meets those requirements must also be outlined in the contract. But the contract should avoid specifying how those performance requirements should be met; the prime contractor should have the ability to decide how best to meet them. Understanding and specifying adequate test procedures is an area where the involvement of the technical community is especially important.

Develop a process to minimize and manage changes. Changes invariably occur during any program. They may crop up in the desired performance of the platform; in the systems and equipment used to achieve performance; in the schedule of the project; or in the responsibilities of the various organizations involved in the design, build, and testing of the platform. Some program changes are beneficial, such as ones in the *Virginia* program that we noted earlier. But other changes may be more disruptive. Therefore, management structures must be in place to deal with any contract changes that are proposed during the conduct of the program. Changes may affect cost, schedule, or capability. It is important that the program office understands the impact of proposed changes and has a procedure in place to approve or reject them. Understanding the impact of proposed changes requires the involvement of the technical community and the cost estimation community as well as the contractor. When funding is limited, changes that result in increased costs must be especially examined.

Establish agreed-upon tracking mechanisms and payment schedules and develop a timely and thorough decisionmaking process. It is important to have an effective system for tracking progress and a payment schedule that is tied to clearly defined milestones and that reserves adequate

[3] Incentives to reduce costs are also important after the contract is signed. The *Virginia* program used a capital expenditure program to fund facility improvements at the shipyards to help lower construction cost.

funds to handle difficulties that occur later in the program. Issues will arise during the conduct of a program, and most of them will require timely decisions. It is important that a program have a decisionmaking process in place, with the appropriate checks and balances, which involves all applicable organizations—the Navy, the technical community, the program office, the SUPSHIP, and the contractor. This process must thoroughly address all the appropriate issues and their impact on cost, schedule, and performance. It must also be timely in addressing those issues so as not to delay the program or add cost.

Designing and Building the Submarines

Many lessons from the three programs described above are also applicable for the design and construction phases of a new program. It is important to get all the right organizations—operators, maintainers, and the technical community—involved throughout a program, to understand how operational requirements affect design and construction, and plan for the appropriate testing of the systems and platform to ensure requirements are met. Therefore, several lessons described below have some repetition with those described previously.

Involve builders, maintainers, operators, and the technical community in the design process. One very important lesson from the *Virginia* program is to use a design/build process during the design of a new submarine. This involves having the builders actively involved in the design process to ensure that what is designed can be built in an efficient manner. The design/build process should go further than merely involving builders in the design. The design should also be informed by operators, key suppliers, maintainers, and the technical community. Therefore, it is important to think of the design team as being a collaboration of submarine draftsmen and design engineers with inputs from those that must build to the design, operate the submarine, and maintain it. This collaboration should extend throughout the duration of the design program. However, throughout the design/build process, it is important to keep in mind that the cost-effectiveness of the post-delivery or ILS period of the submarine is the true design and construction target. While maintenance ease is a desired trait, this must be balanced against long-term maintenance costs.

It is important to not only have the technical community involved in the design process, but also to listen and react to the concerns they may raise. The degree to which existing technology is "pushed" in a new design will affect the risks to cost, schedule, and performance of the end platform. The technical community should understand the state of technology and the degree to which a new design extends that technology.

Include in the design the capability to remove and replace equipment that may become obsolete during the life cycle of the new submarine. The operational life of a submarine platform is typically greater than the life of some of the technologies incorporated in the submarine design. This is especially true for command, control, communications, computing, and intelligence (C4I) equipment. Adequate access paths and removal hatches were included in the *Ohio, Seawolf,* and *Virginia* designs, facilitating the removal and replacement of equipment that requires repair or has become obsolete. The design of the submarine should anticipate the need to remove and replace large pieces of equipment and include access paths and hatches to facilitate such removals. For C4I equipment, standard racks and connections should be incorporated into the design.[4]

Complete the majority of the design drawings before construction begins. One very important lesson for the build of a new submarine is to ensure that the majority of the design drawings are complete before construction begins. There is often a rush to remain on schedule or to show progress to the government or the public. It is far better to delay construction to ensure the design is largely complete rather than risk the costly rework and changes typically resulting from an immature design. Use of three-dimensional product models facilitates the design/build process, but these models must be completed early to support material ordering and downloading of manufacturing data to numerically controlled machinery. Early completion of a three-dimensional product model ensures all pieces fit and minimizes expensive rework.

[4] See Schank et al., 2009, for a discussion of controlling the C4I upgrade costs on ships.

A good rule of thumb is to have the electronic product model finished and 80 percent or more of the detailed design drawings complete when construction begins.

Develop a thorough and adequate testing program. As mentioned previously, a new program must specify not only the desired operational requirements but also the testing procedures that will ensure that those requirements have been met. These procedures should be developed during the design and build portion of the program. Testing should involve the design and build organization(s) as well as the technical community and the Navy.

Planning for Integrated Logistics Support

Although logistics support occurs more than a decade from the initial design of the submarine, early planning for ILS must inform the design and construction of the submarine and the establishment of the facilities, contracts, and procedures to ensure the desired level of operational availability.

Establish and support a strategic plan for ILS during the design phase of a new program. A strategic plan for ILS must be started early in the program, preferably during the design phase. As mentioned in the design and build lessons, personnel from the organizations responsible for maintaining the submarine should be involved in the design process to ensure that what is ultimately built can be efficiently and effectively supported. Funding should be established to develop the ILS plans and should be protected during program execution.

A strategic ILS plan is predicated on (at least) the following tenets:

- Maximize equipment commonality during submarine design through part standardization.
- Support the operational availability target through equipment reliability testing.
- Ensure the need for maintenance ease and accessibility considers the long-term costs involved.

A concept for operating and maintaining the submarine supports the development of the ILS plan. Desired operational availability is part of setting the requirements for the platform and should factor into the design of the platform. The concept of operations must recognize that the submarine will require time for preventive and corrective maintenance and for equipment modernizations. The end result should be a periodic cycle of training, operations, and maintenance that holds throughout the life of the submarine. The development of the concept of operations and maintenance must involve the operators as well as the maintainers.

Development of a maintenance plan requires that the reliability and maintainability of the equipment and the need for corrosion control of the hull be well understood. This involves frequent interactions with the design authorities and the original equipment manufacturers (OEMs) to obtain the needed data and information. It also involves a thorough understanding, informed by a robust database, of the reliability and maintainability of any existing inventory equipment used in the new platform. Data should be underwritten by reliability testing of new equipment through the full mission profile of the new submarine. Program managers should carefully consider the downstream effect of equipment failure and generally be conservative in their approach to requiring equipment reliability testing. Maximizing the use of standard or common systems, equipment, and parts whenever possible in the design can provide valuable insights into reliability and maintenance.

The strategic plan for ILS should include when maintenance, modernization, and training will be performed; where the activities will take place; and which organizations will perform them. Equipment reliability and the need for corrosion control will factor into when maintenance should be performed. Some maintenance will be the responsibility of the crew at the operating base; higher-level maintenance and modernization will be the responsibility of government or private-sector organizations and will be accomplished either at the operating base or at a shipyard. As discussed above, the end result should be a thorough plan for maintenance and modernization throughout the life of the submarine.

Finally, the ILS plan must include provisions for equipment modernization during the operational life of the submarine. It is inevitable that some equipment on the submarine, especially electronic equipment, will require updates. It is important that modernizations be part of the strategic ILS plan. Modernizations may involve the higher-level maintenance organization but will more likely involve the OEMs. Electronic equipment may require time-phased upgrades involving both hardware and software. Setting periodic hardware and software upgrades will establish a drumbeat of modernizations throughout the program.

Establish a planning-yard function and develop a maintenance and reliability database. The original plans for ILS are likely to be modified as experience is gained on the reliability and maintainability of the equipment. Some equipment may require more maintenance than originally thought, while other equipment may prove to be more reliable or easier to maintain. Establishing a planning-yard function that tracks maintenance and establishes future workloads is important to ensure that the right maintenance is done at the right times. This planning-yard function can be performed by a government organization or by a private-sector firm. One function of the planning yard is to monitor and update the database of the maintenance history of the new submarine. Another function is to stay in constant contact with the design authorities and OEMs to understand any changes in the platform or the equipment maintenance requirements and procedures.

Plan for crew training and transition of the fleet. The ILS plan must also include the when, where, and who for training activities. As with maintenance, some training will occur at the operating base while other training will be accomplished at centralized facilities. When establishing the training plan, it is important to consider the transition of personnel to the new submarine class. Typically, the crew assigned to a submarine during construction provides the validation of operating and casualty procedures and instructions. The crew also functions as a system and equipment validation organization for the Navy. The crew serves as the ship's trials and test operator and the acceptance proxy for the submarine force commander. In this regard, crew support should be a high program manager priority.

APPENDIX

Significant Events in the Three Programs

Tables A.1, A.2, and A.3 show significant events in the *Ohio*-class, *Seawolf*-class, and *Virginia*-class programs, respectively.

Table A.1
Significant Events in the *Ohio*-Class Program

Year	Event
1960	Introduction of the Fleet Ballistic Missile System by modifying an attack submarine in construction to a ballistic missile submarine, USS *George Washington* (SSBN 598), fitted to carry 16 Polaris A1 missiles
1967	STRAT-X Study commences
March 1968	ULMS Study commences
1972	Final submission of requirements to Congress
July 1974	Contract for SSBN 726 ship awarded to EB with delivery date of April 1979 and best effort delivery of 1977
July 1974	Construction of lead *Ohio* ship begins
August 1974	SECDEF APDM approves acquisition rate
October 1974	Construction begins on Trident training facility at the Trident Support Site in Bangor, Washington
August 1975	SECDEF APDM approved continuation of Trident Acquisition Program to 11 ships
July–November 1975	Metal Trades Council strike at Electric Boat
September 1976	Acquisition plan changes to 13 ships

Table A.1—Continued

Year	Event
December 1977	Acquisition plan changes to 14 ships
December 1978	Acquisition plan changes back to 13 ships
December 1979	Acquisition plan changes back to 14 ships
August 1980	EB sends letter to Navy alerting it of a delay in the delivery of the first ship from February 1981 to June 1981.
December 1980	Acquisition plan changes to 15 ships
October 1981	First Trident ship, USS *Ohio* (SSBN 726), delivered to the Navy
October 1981	SECDEF PDM directs the Navy to fund development of the D5 missile
November 1981	USS *Ohio* (SSBN 726) and USS *Florida* (SSBN 728) commissioned and launched from EB
April 1982	Decision to incorporate the Trident D5 missile starting with the ninth Trident. Ninth Trident delivery extended one year to December 1988. 10th and 11th ships affected to a lesser extent; 12th and subsequent ships not affected
August 1982	Delivery of USS *Michigan*, SSBN 727
October 1982	USS *Ohio* deployed on her first strategic deterrent patrol
June 1983	Delivery of USS *Florida*, SSBN 728
July 1983	USS *Michigan* deployed
December 1983	Acquisition plan changes to 16 ships
January 1984	Delivery of USS *Georgia,* SSBN 729
September 1984	Delivery of USS *Henry M. Jackson*, SSBN 730
December 1984	Acquisition plan changes to 18 ships
April 1985	Delivery of USS *Alabama*, SSBN 731
November 1985	Delivery of USS *Alaska*, SSBN 732
August 1986	Delivery of USS *Nevada*, SSBN 733
December 1986	Acquisition plan changes to 19 ships
November 1988	First D5-capable submarine delivered (USS *Tennessee*, SSBN 734)

Table A.1—Continued

Year	Event
December 1988	Acquisition plan changes to 21 ships
August 1989	Second D5-capable submarine delivered (USS *Pennsylvania*, SSBN 735)
September 1990	Third D5-capable submarine delivered (USS *West Virginia*, SSBN 736)
December 1990	Acquisition plan changes back to 18 ships
June 1991	Delivery of USS *Kentucky,* SSBN 737
May 1992	Delivery of USS *Maryland*, SSBN 738
June 1993	Delivery of USS *Nebraska*, SSBN 739
June 1994	Delivery of USS *Rhode Island*, SSBN 740
June 1995	Delivery of USS *Maine*, SSBN 741
June 1996	Delivery of USS *Wyoming*, SSBN 742
August 1997	Delivery of last *Ohio*-class submarine, USS *Louisiana*, SSBN 743

Table A.2
Significant Events in the *Seawolf*-Class Program

Year	Event
July 1982	SSN 21 class submarine program begins with establishment of Group Tango to assess the need for an advance technology submarine
December 1982	NAVSEA directed by CNO to conduct feasibility studies
June 1983	Conceptual design approved by SECNAV
December 1983	Preliminary design approved by SECNAV and SECDEF
May 1985	Preliminary design phase completed
1986	Contract design contracts completed with Newport News and EB
April 1987	Detailed design contract with Newport News as lead design yard signed
January 1989	Contract awarded to EB for SSN 21
October 1989	Ship construction for SSN 21 commenced

Table A.2—Continued

Year	Event
May 1991	Contract awarded to EB for SSN 22
July 1991	Court declares the SSN 22 construction contract void
December 1991	29-ship class reduced to two hulls. Construction profile restructured due to the end of the Cold War
December 1991	EB and the Navy reach agreement for delayed delivery of SSN 21 from May 1995 to May 1996 due to faulty HY-100 welds. New $788.2 million target price set
February 1991	Stop work orders issued on all active contracts for SSN 22 and later ships
January 1992	*Seawolf* program terminated
June 1992	PL 102-298 reinstates SSN 22
June 1992	Stop orders on SSN 22 lifted
September 1992	SSN 22 construction commences
June 1995	*USS Seawolf,* SSN 21*, launch date*
June 1996	SSN 21 successfully completes dock trials
June 1996	Contract for SSN 23 awarded
July 1996	SSN 21 successfully completes Alpha sea trials
September 1996	SSN 21 sustains damage to its wide-aperture array during Bravo sea trials
March 1997	SSN 21 successfully completes Charlie sea trials
June 1997	SSN 21 successfully completes Delta sea trials
July 1997	USS *Seawolf*, SSN 21, commissioned
September 1997	USS *Connecticut*, SSN 22, launched
December 1998	USS *Connecticut*, SSN 22, commissioned
May 2004	USS *Jimmy Carter*, SSN 23, launched
February 2005	USS *Jimmy Carter,* SSN 23, commissioned

SOURCES: Selected Acquisition Report, SSN-21 Class/BSY-2, December 31, 1991; December 31,1993; and December 31, 1997; *Naval Vessel Register*, no date.

Table A.3
Significant Events in the *Virginia*-Class Program

Year	Event
February 1992	CNO memo stating *Virginia* requirements
August 1992	Under Secretary of Defense Acquisition signs the New Attack Submarine Acquisition Decision Memorandum approving concept studies (Milestone 0)
August 1994	Defense Acquisition Board approves New Attack Submarine Milestone 1, initiating the new attack submarine design and build program with construction beginning at EB in FY98
June-July 1995	Ship specifications approved; Milestone 2 completed
January 1996	New Attack Submarine IPPD contract awarded
February 1996	FY96 NDAA directs that the first four ships of the NSSN program be split between EB and NNS
December 1996	EB and NNS propose to build first four ships as a team rather than competitors
February 1997	EB/NNS coproduction agreement signed and low-rate initial production authorized
September 1998	Four-ship NSSN construction contract issued for $4.2 billion
October 2004	USS *Virginia* (SSN 774) delivered
October 2004	USS *Virginia* (SSN 774) commissioned
June 2006	USS *Texas* (SSN 775) delivered
September 2006	USS *Texas* (SSN 775) commissioned
December 2006	USS *Hawaii* (SSN 776) delivered
May 2007	*USS Hawaii (SSN 776) commissioned*
February 2008	USS *North Carolina* (SSN 777) delivered
May 2008	USS *North Carolina* (SSN 777) commissioned
August 2008	USS *New Hampshire* (SSN 778) delivered
October 2008	USS *New Hampshire* (SSN 778) commissioned
December 2008	Navy awards contract to General Dynamics Electric Boat (and Northrop Grumman Newport News through the teaming agreement) for the construction of eight *Virginia*-class submarines from FY09 through FY13

Table A.3—Continued

Year	Event
December 2009	USS *New Mexico* (SSN 779) delivered
March 2010	USS *New Mexico* (SSN 779) commissioned

NOTE: NNS = Newport News Shipbuilding.

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